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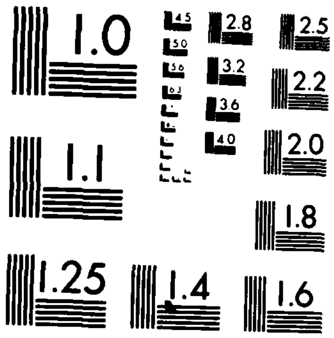

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By Frank Dellaripa
and James A. Bailard
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Studies of Scour Patterns Produced by Rotating Jets in a Flow Field

ABSTRACT **A series of laboratory experiments were conducted to determine the scouring properties of submerged jets. Five cases were considered: (1) a jet rotating in still water; (2) a fixed jet in a fluid moving parallel to the jet (coflow); (3) a fixed jet in a fluid moving perpendicular to the jet (crossflow); (4) a fixed jet in a fluid moving against the jet (counterflow); and (5) a jet rotating in a moving fluid. In each case, dimensionless equations were developed to estimate the applied shear stress at the bed as a function of distance from the jet. The test results showed that a fixed coflow jet scoured the greatest distance, and rotating a jet in a mean flow scoured the greatest area. A summary of test results for each jet/current combination is provided in tabular form.**

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

METRIC CONVERSION FACTORS

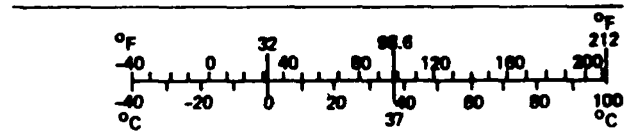
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A series of laboratory experiments were conducted to determine the scouring properties of submerged jets. Five cases were considered: (1) a jet rotating in still water; (2) a fixed jet in a fluid moving parallel to the jet (coflow); (3) a fixed jet in a fluid moving perpendicular to the jet (crossflow); (4) a fixed jet in a fluid moving against the jet (counterflow); and (5) a jet rotating in a moving fluid. In each case, dimensionless equations were

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developed to estimate the applied shear stress at the bed as a function of distance from the jet. The test results showed that a fixed coflow jet scoured the greatest distance, and rotating a jet in a mean flow scoured the greatest area. A summary of test results for each jet/current combination is provided in tabular form.

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A series of laboratory experiments were conducted to determine the scouring properties of submerged jets. Five cases were considered: (1) a jet rotating in still water; (2) a fixed jet in a fluid moving parallel to the jet (coflow); (3) a fixed jet in a fluid moving perpendicular to the jet (crossflow); (4) a fixed jet in a fluid moving against the jet (counterflow); and (5) a jet rotating in a moving fluid. In each case, dimensionless equations were developed to estimate the applied shear stress at the bed as a function of distance from the jet. The test results showed that a fixed coflow jet scoured the greatest distance, and rotating a jet in a mean flow scoured the greatest area. A summary of test results for each jet/current combination is provided in tabular form.

CONTENTS

INTRODUCTION

Maintenance dredging of unwanted sedimentation in harbor berthing areas represents a serious problem for the Navy. The highest rates of sedimentation typically occur in quiet-water areas such as along quay walls and within cul-de-sac berths. These areas also have higher dredging costs due to their restricted access.

Scour jet arrays represent a new method of dealing with unwanted sedimentation in harbor berthing areas. Each array is designed to prevent or reduce sedimentation within one or more berths. An array consists of a series of underwater jets powered by a conventional water pump (Figure 1). Flow from the pump is sequentially fed to each jet for a period of 5 to 10 minutes at the start of ebb tide. The scouring action of the jets acts to resuspend newly deposited flocculated clay sediments; the ebbing current sweeps the sediment out of the berthing area.

Previous laboratory and field experiments have shown that the scouring action of a fixed submerged wall-mounted jet is a function of the jet diameter, the jet discharge rate, and the jet orientation relative to the bottom. Van Dorn et al. (Ref 1) conducted a series of experiments to determine the scour pattern associated with a fixed, bottom-mounted scour jet oriented parallel to the bottom. Van Dorn used a thin layer of diatomaceous earth (DE) (threshold stress = 1 dyne/cm^2) to observe the variation in scour distance and scour width as a function of jet diameter and jet discharge rate. He found that the jet scour pattern was tear drop in shape with the maximum width, y_m, approximately 1/3 of the maximum scour distance, r_m (Figure 2). Jenkins et al. (Ref 2) generalized these results, producing a dimensionless equation which predicts the applied shear stress at the bottom as a function of distance from the jet, jet diameter, and jet discharge rate (Appendix A).

Bailard and Camperman (Ref 3) conducted additional scour jet experiments examining two factors: the vertical elevation of the jet nozzle, and the angle of the jet nozzle relative to the horizontal (Figure 3). These tests showed that the maximum scour distance was achieved with a slightly elevated jet having a small downward angle. They developed a dimensionless scour equation similar in form to the equation by Jenkins et al. (Ref 2), but including jet elevation and jet angle as independent variables (Appendix A).

Existing design procedures for a scour jet array system assume fixed jets operating in a still fluid. While a number of jet array systems have been designed using these procedures, additional improvements are needed to insure more effective system performance. For example, field tests indicate that tidal currents moving across the discharge path of a jet may significantly reduce the scour distance of the jet. Alternatively, tidal currents moving in the same direction as the jet discharge may enhance the scour distance. Tests are needed to quantify these mean current effects so that the design scour distance is achieved under realistic operating conditions.

A second shortcoming in existing design procedures is the limitation posed by fixed scour jets. Simple geometry suggests that a scour jet array fitted with rotating jet nozzles might significantly reduce overall system costs. In theory, a rotating jet can cover approximately ten times the area of a fixed jet using the same amount of hardware and energy. Before this concept can be evaluated, tests are needed to quantify the effects of jet rotation rate on scour distance.

Recognizing the potential benefits of improved scour jet array design procedures, the Naval Facilities Engineering Command (NAVFAC) funded the Naval Civil Engineering Laboratory (NCEL) to conduct an experimental investigation to determine the behavior of rotating and fixed jets in moving fluids.

OBJECTIVE

The overall objective of the experimental investigation was to evaluate the effects of a steady current and jet rotation rate on the

performance of a submerged scour jet as a means of improving design procedures for scour jet array systems. Specific objectives included: observing the scour patterns of a rotating jet in the laboratory (with and without a mean current); observing the scour patterns of a fixed jet in a steady current; and developing equations to predict the scour patterns of fixed and rotating jets in steady currents. The performance of a fixed jet in a still fluid was not considered, having already been studied in detail by Van Dorn et al. (Ref 1) and Bailard and Camperman (Ref 3).

APPROACH

The ideal approach to the stated problem would be to start from first principals and derive analytic expressions describing the distribution of shear stress associated with a submerged, near-bottom wall jet (i.e., a scour jet). A series of experiments could then be performed to verify these relationships and supply the necessary experimental coefficients. Unfortunately, the complexity of the flow field associated with a scour jet (rotating or fixed) in a mean current places this type of approach well outside the scope of the present investigation.

In the present investigation, an empirical approach was taken consisting of a series of small scale laboratory experiments with fixed and rotating scour jets in a mean current. The results from these experiments were then generalized for full-scale applications based on the work by Van Dorn et al. (Ref 1), Jenkins et al. (Ref 2), and Bailard and Camperman (Ref 3). The approach used in analyzing the experimental data was to seek a series of dimensionless coefficients which could be applied to the estimated scour distance for a fixed jet in a still fluid. This would correct for the effects of mean current and jet rotation. These coefficients were expressed as a function of the dimensionless mean current and rotation rate.

The investigation consisted of two parts. In Part I, scour patterns were generated with a jet rotating in still water (no current). Independent variables included: jet rotation rate, jet discharge rate,

jet angle relative to the horizontal, and jet elevation above the bed. In Part II, scour patterns were generated with fixed and rotating jets in a moving fluid. For the fixed jets, independent variables included mean current velocity, jet discharge rate, and jet orientation. For the rotating jet, independent variables included mean current velocity, jet discharge rate, and jet rotation rate. In all cases with nonzero current, the jets were positioned horizontally, flush with the bottom.

EXPERIMENT INVESTIGATION - PART I

Equipment Test Setup For Rotating a Jet in Still Water

The jet assembly consisted of a 5-foot long, 3/4-inch brass pipe connected to a 4-inch long, 3/8-inch ID brass pipe by a reducing elbow (Figure 4). The 3/8-inch ID pipe served as the jet nozzle rotating in a horizontal plane. A protractor was used to adjust the jet nozzle angle (θ) at the elbow (Figure 3 shows the jet nozzle angle). Two greased pillow blocks allowed the raising or lowering of the jet nozzle in the vertical plane and provided smooth rotation.

A high torque, variable speed motor connected to a chain drive rotated the jet assembly; the jet nozzle rotation rate was controlled from the working deck by a throttle cable. The actual rotation rate during each test was measured by timing a fixed number of revolutions. A water swivel attached to the top of the 5-foot pipe prevented the supply hose from becoming twisted.

All tests were peformed in NCEL's 30-foot diameter Seawater Dive Tank. The motor and jet assembly were clamped to a 4-foot square by 3-foot high table placed on the tank floor. The water level was raised to 2.5 feet; enough to submerge the nozzle in 1 foot of water. The test bed was a 4- by 8-foot (122- by 244-cm) sheet of galvanized metal with a 5-cm yellow grid painted on the galvanized surface (Figure 4).

A pump driven by a 5-hp motor provided controlled flow to the jet assembly. The test tank served as a reservoir supplying seawater through a 4-inch diameter suction hose to the pump located on deck. The seawater

passed through a flowmeter manifold (one 12 gpm and one 2.2 gpm) then discharged through the jet nozzle (Figure 5). The flowmeters were calibrated by measuring the filling time of a known volume.

Diatomaceous earth (DE) was used to indicate bed stress. Previous tests by Van Dorn et al. (Ref 1) had shown DE to have a threshold movement stress of 1 dyne/cm^2. One quart of DE was mixed in an 8-foot long by 6-inch wide enclosure that rested over the test grid. Once the DE had settled (about 5 minutes), the enclosure was removed from the water to begin the tests.

Test Procedures For Rotating a Jet in Still Water

Preliminary tests were conducted to determine the following limits for the experiment:

1. The maximum jet discharge rate from a fixed jet that scoured DE completely off the test bed. Scouring the DE off the test bed left nothing to measure; this test defined an upper limit of the discharge rate for the experiment.

2. The maximum jet rotation rate above which no change in scour radius occurred. A high rotation rate resulted in a small scour radius but as the rotation rate descreased the scour radius increased. This test defined the point where the scour radius reached an equilibrium.

3. The jet discharge and rotation rate combination that produced the smallest scour radius. The time consuming effort of lowering the enclosure into the water needed to be minimized to deposit DE for each test. The approach was to scour a small radius for the first test and gradually increase the scour radius with each additional test without adding DE. This defined the starting point for each individual test in the experiment.

The results showed that fixed jet discharge rates greater than 8 gpm caused DE to scour off the end of the test bed. Jet rotation rates greater than 2 rpm produced no change in scour radius. Test results also showed a 2-gpm jet discharge rate combined with a 2-rpm jet rotation rate produced the smallest scour radius. These two values (2 gpm and 2 rpm) were applied at the beginning of each test to ensure a common starting point. For the next test, without adding DE to the water, the discharge rate was increased and the rotation rate decreased; this produced a larger scour radius.

Based on the above findings and the work conducted by Bailard and Camperman (Ref 3), the following independent variable sets were evaluated:

1. Jet discharge rate (2, 5, and 8 gpm)

2. Jet rotation rate (0, 1/2, 1, and 2 rpm)

3. Jet angle measured downward from the horizontal (0, 5, and 15 degrees)

4. Jet height above the scour surface (0, 7.5, and 15 cm)

The jet nozzle and height pairs were selected from previous test results (Ref 3): 0 degrees, 0 cm; 5 degrees, 5 cm; 15 degrees, 15 cm.

Three jet discharge rates and four jet rotation rates (no rotation included) for each jet angle and height pair were evaluated. The following procedures were applied for each test:

1. Adjust equipment to produce independent variables with starting values of 2 gpm, 2 rpm, 0 degrees, and 0 cm.

2. Lower the DE enclosure over the test bed.

3. Add a quart of DE to the water in the enclosure.

4. Mix the water and DE together.

5. Wait 5 minutes then remove the enclosure from the water.

6. Turn on the pump and variable speed motor to commence scouring.

7. After 10 minutes, record the maximum scoured radius and width.

8. Adjust the equipment to produce a discharge rate and jet rotation rate (e.g., 5 gpm, 2 rpm, and 0 degrees, 0 cm).*

9. Continue to test the rates for (0 degrees, 0 cm).

The data from Part I is tabularized in Appendix B.

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*The section on Equipment Test Setup for Rotating a Jet in Still Water describes how these adjustments were made.

EXPERIMENT INVESTIGATION - PART II

Equipment Test Setup for a Fixed or Rotating Jet in a Current

The same test equipment from Part I was used in Part II, except for the addition of a flow channel, which was 15-feet long by 2-feet high by 8-feet wide (Figure 6). A 30-inch diameter centrifugal pump controlled by a 12-hp hydraulic power source was used to generate flow in the channel. Figure 6 shows the pump orientation and direction of flow. The channel was supported in the NCEL dive tank by an overhead gantry crane; the still water level in the channel was 18 inches. The variable speed motor and jet assembly from Part I were installed as shown in Figure 7.

The channel currents were monitored with a Marsh McBirney electromagnetic current meter hardwired to a deck readout box. The current meter location can be seen in Figure 7. DE was mixed into the water bounded by the channel walls and after 5 minutes the DE had settled and testing could begin.

Test Procedures For a Fixed or Rotating Jet in a Current

The experiment consisted of four channel flow conditions, combining either a fixed or rotating jet with a constant jet angle and jet height (0 degrees, 0 cm).* The following channel flow conditions were applied:

1. Coflow - flow in the same direction as the jet stream.
2. Crossflow - flow perpendicular to the jet stream.
3. Counterflow - flow opposing the jet stream.
4. A jet rotating in uniform flow.

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*Past test results for fixed jets in still water showed (0 degrees, 0 cm) jet orientation promoted nearly maximum scour (Ref 3).

Prior to conducting tests, the minimum current velocity required to resuspend DE with no jet stream was experimentally determined. Too fast a current would have removed DE independent of the jet stream. To verify this, a thin layer of DE was deposited on the channel grid. The current flow was gradually increased until insipient motion of the DE occurred. The point of insipient motion defined the upper limit for current induced scour and was found to be 0.35 fps.

Based on the above result, mean current magnitudes of 0.1, 0.2, and 0.3 fps were selected for the scour jet tests.

We chose jet discharge rates and jet rotation rates from the test results in Part I which were 2 and 4 gpm, and 1/2 and 1 rpm. The following independent variable sets were applied in Part II:

1. Three current magnitudes (0.1, 0.2, and 0.3 fps).
2. Two jet discharge rates (2 and 4 gpm).
3. Two jet rotation rates (1/2 and 1 rpm) including a fixed jet.
4. Four different jet orientations in the flow channel.

The following procedures were applied for the coflow tests:

1. Center the variable speed motor and jet assembly at the entrance to the flow channel (Figure 7).
2. Adjust the fixed jet discharge to 2 gpm, and the current velocity to 0.1 fps.
3. Operate the jet for 10 minutes, then record the results.
4. Repeat steps 2 and 3 with current velocities of 0.2 and 0.3 fps.
5. Adjust the fixed jet discharge to 4 gpm and test with the three current velocities.

The jet assembly was moved to one side of the channel for the crossflow tests. All three current velocities and two jet discharge rates were tested with the fixed jet pointing perpendicular to the flow (Figure 8). The counterflow tests consisted of the same current velocities

and fixed jet discharge rates; however, they opposed each other (Figure 9). For the rotating jet tests, the jet assembly was positioned in the center of the channel as shown in Figure 9, but the jet rotates. Jet rotation rates (1/2 and 1 rpm) were examined with the three current and the two jet discharge rates.

DATA ANALYSIS

The design of a scour jet array system depends critically on the distribution of bottom stress imposed by the submerged jets. Van Dorn et al. (Ref 1) and Jenkins et al. (Ref 2) derived a simple equation to predict the shear stress distribution for a fixed, bottom-mounted, horizontal jet or arbitrary size operating in still water. Results from the present study show that this distribution is changed when the jet is rotated or when the surrounding fluid is in motion.

In order to account for the effects of mean currents and jet rotation on the scour pattern associated with a scour jet, dimensionless expressions were sought for a series of modification coefficients using a least squares estimation procedure. The modification coefficients were defined as the ratio of the observed scour distance divided by the scour distance for an equivalent fixed jet operating in a still fluid. Thus, in the case of the maximum scour radius, r_m, the modification coefficient, K, was defined as

$$K = \frac{r_m}{r_{m_o}} \qquad (1)$$

where r_m is the observed maximum scour radius corresponding to a type of jet/flow condition and r_{m_o} is the scour distance for a particular fixed jet operating in a still fluid. A similar expression was derived from the width of the jet, where the modification coefficient, J, becomes

$$J = \frac{y_m}{y_{m_o}} \quad (2)$$

where y_m is the observed maximum scour width corresponding to a particular jet/flow condition and y_{m_o} is the corresponding width for a fixed jet operating in still water.

The basic concept of this approach was that the fixed jet/still water scour distance could be predicted from existing equations (see Appendix A), while the modification coefficients could be expressed as simple functions of the jet/current parameters. Combining the two, the modified scour distance could then be predicted from known jet/current parameters.

Modification coefficients were developed for the following cases:

1. A rotating, horizontal bottom jet in still water (scour radius only).
2. A fixed, horizontal bottom jet in a coflow current (scour radius only).
3. A fixed, horizontal bottom jet in a crossflow current (scour radius and scour width).
4. A fixed, horizontal bottom jet in a counterflow current (scour radius and scour width).
5. A rotating, horizontal bottom jet in a current (scour radius at each quandrant).

The approach used in each case was to plot the modification coefficient as a function of the following dimensionless variables:

1. The dimensionless rotation rate, $\omega = \omega_o d/U_o$
2. The dimensionless mean current, $\beta = \bar{u}/U_o$
3. The dimensionless undisturbed (i.e., fixed jet/still fluid) scour distance, r_{m_o}/d

where ω_o is the jet rotation rate, d is the jet diameter, U_o is the jet discharge velocity, and $\bar{u}$ is the mean current velocity.

In most cases, visual inspection of the experimental data plots suggested the appropriate form for an equation describing the modification coefficient. A multiple linear regression technique was then used to estimate all undetermined parameters in the equations. One constraint in this procedure was that each equation had to be expressed as a linear function of its undetermined parameters (often after suitable transformation). More specific details of this procedure are discussed below.

Rotating a Jet in Still Water

Tests of a jet rotating in still water showed the scour radius to be a strong function of the rotation rate. Increasing the rotation rate of the jet caused a sharp decrease in the resulting scour radius. This effect gradually decreased with increasing rotation rate, with the modification coefficient eventually approaching a constant value.

Figure 10 is a plot of the rotation modification coefficient, K_ω, as a function of the dimensionless rotation rate, ω. Visual inspection of the data shown in Figure 10 coupled with a simple momentum flux analysis led to the following equation for K_ω:

$$K_\omega = \left(12-11e^{-18\omega}\right)^{-0.417} \tag{3}$$

In the above equation, the coefficients -18 and -0.417 were least squares estimated from the data, while the coefficients -11 and 12 were derived from the momentum flux analysis. Equation 3 is plotted in Figure 10, showing a relatively good fit to the overall trend in the data (coefficient of determination R^2 = .83). A complete summary of this data may be found in Appendix B.

Fixed Jet/Coflow Current

Tests with a fixed jet oriented parallel to the current (coflow) showed the maximum scour radius to increase with increasing mean current strength, and the maximum scour width to decrease with increasing mean current strength. The rate of increase in the scour radius was found to be a function of the flowrate of the jet, alternatively expressed as the scour distance ratio, r_{m_o}/d. The experimental data on the width of the jet were insufficient for analysis.

Figure 11 shows a plot of the coflow modification coefficient, K_{co}, as a function of the dimensionless mean current, β, and the jet flowrate. Visual inspection of the data coupled with dimensional analysis led to the following equation:

$$K_{co} = 1 + 0.913\,\beta^{1.57}\left(\frac{r_{m_o}}{d}\right)^{0.885} \qquad (4)$$

The coefficients 0.913, 1.57, and 0.885 were least squares estimated from the experimental data. Equation 4 is shown plotted in Figure 11 as two lines, one corresponding to a jet discharge rate of 2 gpm and the other to a jet discharge rate of 4 gpm. The fit is judged to be good for the latter case ($R^2 = 0.98$) and somewhat poor for the former case ($R^2 = 0.79$). All of the data plotted in Figure 11 are summarized in Appendix C.

Fixed Jet/Crossflow Current

Tests of a fixed jet in a cross current were surprising. Before testing it was anticipated that a cross current would enhance the scour distance of a fixed jet. In fact, test results showed that the scour distance of the jet decreased with increasing current strength. In contrast to the coflow situation, changing the jet flow rate had relatively little effect on the modification coefficient.

Figure 12 shows a plot of the crossflow modification coefficient, K_{cr}, plotted as a function of the dimensionless mean current strength, β, and the jet discharge rate. Visual inspection of the data suggested an equation which was cubic in the variable β and independent of the discharge rate. A polynomial regression fit to the experimental data led to the following equation for K_{cr}:

$$K_{cr} = 1 + 41.4\ \beta - 3{,}310\ \beta^2 + 46{,}900\ \beta^3 \qquad (5)$$

Figure 12 contains a plot of Equation 5. The fit to the data is excellent ($R^2 = 0.98$).

Figure 12 also shows a plot of the crossflow scour width modification coefficient, J_{cr}, as a function of the dimensionless mean current strength and the jet discharge rate. Again, the coefficient is seen to be principally a function of the mean current strength, β, but not the discharge rate. Visual inspection of the data coupled with a polynomial regression fit to the data led to the following equation:

$$J_{cr} = 1 + 120\ \beta - 7{,}330\ \beta^2 + 104{,}000\ \beta^3 \qquad (6)$$

The fit to the data is relatively good ($R^2 = 0.83$). The crossflow current also induces a deflection of the jet scour pattern. Figure 12 shows a plot of this deflection angle, θ_{cr}, expressed in radians, as a function of the dimensionless mean current strength and the jet discharge rate. Visual inspection of the data coupled with regression analysis led to the following equation which is quadratic in β and independent of the jet discharge rate:

$$\theta_{cr} = -4.64\ \beta + 612\ \beta^2 \qquad (7)$$

The fit to the data is adequate ($R^2 = 0.72$). All of the data contained in Figure 12 are summarized in Appendix C.

Fixed Jet/Counterflow Current

Counterflow currents were found to significantly diminish the scour radius of a submerged jet. At the same time, the width of the jet was enhanced. Figure 13 shows a plot of the counterflow scour radius modification coefficient, K_{ct}, as a function of the dimensionless mean current strength and the jet discharge rate. Visual inspection of the plotted data coupled with regression analysis led to the following equation which is a function of both β and the undisturbed dimensionless scour radius:

$$K_{ct} = 1 + 1.75\ \beta^{-0.228} \left(\frac{r_{m_o}}{d}\right)^{-0.336} \tag{8}$$

where the coefficients 1.75, -0.228, and -0.336 were least squares estimated from the experimental data. Equation 8 is shown plotted as two lines in Figure 13; the lines refer to a 2 gpm and 4 gpm jet discharge rate. The fit to the data is excellent ($R^2 = 0.93$).

Following a similar procedure, Figure 14 shows a plot of the counter-flow jet width modification coefficient, J_{ct}, as a function of the dimensionless mean current strength, β, and the jet discharge rate. Visual inspection of the data and application of multiple regression analysis led to the following equation:

$$J_{ct} = 1 - 0.0161\ \beta \left(\frac{r_{m_o}}{d}\right)^{1.43} + 0.003\ \beta^2 \left(\frac{r_{m_o}}{d}\right)^{2.43} \tag{9}$$

Equation 9 is shown plotted in Figure 14 for a 2 and 4 gpm discharge rate. The fit to the data is excellent ($R^2 = 1.0$). The data plotted in Figures 13 and 14 are summarized in Appendix C.

Rotating a Jet in a Steady Current

Tests of a rotating jet in a mean current showed the current to cause a distortion in the jet scour pattern. What was originally a

circular scour pattern became a diamond-shaped pattern as the mean current increased. This distortion has been characterized by the four quandrant radii (i.e., the radius in line with the mean current, the radius counter to the mean current, and the radii perpendicular to the mean current). Interestingly, the latter were found to be unequal, due to the rotation of the jet.

Tests were conducted by varying the jet discharge rate, the jet rotation rate, and the mean current velocity. Values for each parameter are summarized as follows:

Jet Flowrate (gpm)	Jet Rotation Rate (rpm)	Mean Current (cm/sec)	Case Number
2	0.90	0	1
2	0.90	38.1	1
2	0.90	68.6	1
2	0.90	99.1	1
4	0.90	0	2
4	0.90	38.1	2
4	0.90	68.6	2
4	0.90	99.1	2
2	0.53	0	3
2	0.53	38.1	3
2	0.53	68.6	3
2	0.53	99.1	3
4	0.53	0	4
4	0.53	38.1	4
4	0.53	68.6	4
4	0.53	99.1	4

Figures 15, 16, 17, and 18 contain plots of the four modification coefficients, K_{rc1}, K_{rc2}, K_{rc3}, and K_{rc4} as a function of the dimensionless current strength and the above-mentioned case numbers. Note that the coefficients are numbered consecutively moving in a clockwise direction, starting in the direction of the mean current. The modification coefficients plotted in Figures 15 through 18 are defined somewhat differently than for the rotating jet, zero current case. Instead of being nondimensionalized by the fixed jet, zero current scour radius; they are nondimensionalized by the rotating jet, zero current scour radius, i.e.,

$$K'_{ri} = \frac{r_{m_i}}{r_{m_{oi}}} \qquad (i = 1, 2, 3, 4) \tag{10}$$

If K_{ri} is the modification coefficient as originally defined, then

$$K_{ri} = K'_{ri}\, K_r \qquad (i = 1, 2, 3, 4) \tag{11}$$

Plotting the data in terms of K'_{ri} was found to be a convenience since it removed the effects of rotation and jet discharge.

Visual inspection of the data plotted in Figures 15, 16, 17, and 18 coupled with regression analysis led to the following equation in the parameter β:

$$K_{ri} = (1 + A\,\beta^3 + B\,\beta^2 + C\,\beta) \left(\frac{1}{12 - 11\,e^{-18\omega}}\right)^{0.417} \tag{12}$$

where

i	A	B	C	R^2
1	-6,666	503	-00.6	0.85
2	-2,701	372	-20.2	0.90
3	-2,356	316	-16.5	0.84
4	-7,206	500	-12.9	0.79

The above values of R^2 indicate a relatively good fit to the data.

Appendix C contains a summary of all the data plotted in Figures 15 through 18.

DISCUSSION

The test results show that the scour radius of a submerged jet is a function of the jet rotation rate and the velocity of the surrounding

fluid. For rotating jets, reducing the rotation rate increases the scour distance while increasing the time to complete one revolution. Depending on the erosional characteristics of the sediment, there should be an optimum rate of rotation which will produce the greatest sedimentation protection for the least amount of energy. From a practical standpoint, however, for typical field conditions (i.e., jets having a scour radius of approximately 75 feet), rotation rates of 0.5 to 1.0 rpm should produce less than a 5% reduction in scour radius.

While most of the laboratory tests of scour jets have been conducted in still water, most scour jet arrays operate in either a coflow or crossflow condition. For the jet array systems tested at Mare Island Naval Shipyard (Jenkins et al. Ref 2), velocity ratios (B) ranged from 0.01 to 0.02. The present tests show that for coflow jets, scour radii can be enhanced from 5 to 15% by the presence of the mean current. For crossflow jets, scour radii are changed less than 5%, while scour widths are increased from 30 to 40%. The deflection angles are typically less than 10 degrees.

The present tests show that the presence of a mean current reduces the relative advantages of a rotating jet over a fixed jet. Nevertheless, under typical field conditions (i.e., jets having a scour radius of 75 feet and mean currents of about a knot or less), the relative advantage of a rotating jet over a fixed jet is about a factor of 7.

The present test results are subject to a number of limitations. For example, the two-dimensional scour patterns produced by the resuspension of a thin layer of DE are only partially representative of scour conditions in the field. In harbor berthing areas, the bottom is composed of relatively soft clay sediments. The scouring action of the submerged jets will create a three-dimensional depression in the bottom, thereby modifying the hydrodynamics of the scour jet flow. Under such circumstances, the plan dimensions of the scour depression may be considerably different than the predicted dimensions.

Another limitation of the present tests was the constant jet diameter. Although changing the jet diameter may have some effect on the predicted results, this effect is thought to be negligible.

The results of the present laboratory study will be verified through comprehensive testing of a full scale prototype system to be installed at Mare Island Navy Shipyard (MINSY). The test bed has been designed to systematically vary the jet discharge rate, the jet diameter, the jet elevation, and the jet angle. Rotating jets as well as fixed jets will be examined.

The scour jet array test bed at MINSY will consist of 13 jets and will be powered by a vertical turbine pump. Flow to each jet will be controlled by a separate butterfly valve connected to a common manifold. The pneumatically-actuated valves will be sequenced by a digital control system which will also act as a data logger and monitoring system. The system will be installed at Berth 9 along a 200-foot section of quay wall. Monitoring of the system will begin in FY87 and continue through FY88.

CONCLUSIONS

A series of experiments were conducted to determine the effects of rotation rate and mean current strength on the scour distance behavior of submerged jets. The scour distance of a jet was found to decrease with increasing rotation rate of the jet. Although the greatest scour distance occurs with a fixed jet, a rotating jet can scour a greater area. For most field applications of the scour jet arrays, rotation rates of 1/2 to 1 rpm are optimum.

The effect of a mean current on fixed and rotating jets was found to be a function of the orientation and discharge velocity of the jet relative to the mean current. For jets directed with the current (coflow), the relative scour distance was increased. Increasing the jet velocity relative to the mean current was found to reduce the effect of the mean current.

A series of equations were developed to predict the effects of mean current and jet rotating on the scour pattern for a jet. Dimensionless coefficients defined as the ratio of the maximum scour distance (with steady currents and/or jet rotation) divided by the scour distance for

an equivalent fixed jet in a still fluid are expressed as functions of the dimensionless current strength, the dimensionless rotation rate, and the dimensionless scour distance. Although based on laboratory data, similar studies suggest that these equations will be valid for prototype-sized jets as well. Table 1 contains a useful summary of these experimental results.

These equations form the basis for a significant improvement in existing design procedures for scour jet array systems. The ability to estimate the effect of mean currents on the maximum scour distance of a jet will ensure acceptable system performance and more optimum system design. Incorporation of rotating scour jet nozzles into existing design practice holds the promise for significant reductions in system costs.

One of the remaining uncertainties in the design procedure for a scour jet array is the minimum shear stress needed to resuspend newly deposited flocculated clay sediments. Laboratory experiments suggest that a stress of about 0.004 psf should be adequate; however, this value needs to be better defined. NCEL is currently developing a Shear Test Device which can be deployed at a site to determine the minimum necessary shear stress. Initial testing of this device looks promising.

A full scale scour jet array test bed is currently being installed at MINSY for the purpose of evaluating component and system performance. The test bed will be used to systematically examine the effects of jet flowrate, jet height, and jet angle on the scour distance of a jet. The results of these tests will be used to evaluate the predictive equations presented in this report.

REFERENCES

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2. Scripps Institute of Oceanography. Reference Series No. 81-22: The evaluation of sediment management procedures, Phase IV-VI final report, 1978-1980, by S.A Jenkins, D.L. Inman, and W.G. Van Dorn (1981). La Jolla, Calif., 1981.

3. Naval Civil Engineering Laboratory. Technical Report R-899: A design for a test bed scour array for Mare Island Naval Shipyard, by J.A. Bailard and J.M. Camperman. Port Hueneme, Calif., May 1983.

Table 1. Summary of Jet Stream/Current User Information

Jet Stream/Current	K	J	Scour Pattern	Application	Advantage	Disadvantage
Fixed Jet/Coflow	$1 + 0.913\beta^{1.57}\left(\frac{r_{m_o}}{d}\right)^{0.885}$	Insufficient data	Long, narrow	Quay berths for small ships Finger berths branching off rivers	Requires fewer jets to scour along a quay wall Requires a minimum discharge rate to scour efficiently Works well in small currents	The resulting scour paths are too narrow for large ships
Fixed Jet[a]/ Crossflow	$1 + 41.1\beta - 3{,}130\beta^2 + 46{,}900\beta^3$	$1 + 120\beta - 7{,}330\beta^2 + 104{,}000\beta^3$	Medium, deflected towards the current	Quay berths for large ships Docks along rivers Finger berths branching off rivers	Scours sediment a wide distance out from the quay piles	Requires high currents Requires high discharge velocities to scour efficiently Requires more jets to scour the same quay wall length compared to coflow jets.
Fixed Jet/ Counterflow	$1 + 1.75\beta^{-0.228}\left(\frac{r_{m_o}}{d}\right)^{-0.336}$	$1 - 0.0161\beta\left(\frac{r_{m_o}}{d}\right)^{1.43} + 0.003\beta^2\left(\frac{r_{m_o}}{d}\right)^{2.43}$		None		
Rotating Jet/ Current	$(A\beta^3 + B\beta^2 + C\beta + 1) \times \left(\frac{1}{12 - 11e^{-18\omega}}\right)^{0.417}$ *for no current $(A\beta^3 + B\beta^2 + C\beta) = 0$	N/A	Circular, diamond shaped	Docking locations for large ships Finger berths branching off rivers Bays and estuaries	Requires fewer jets compared to other scouring systems Removes more sediment per area compared to other systems Versatile, useful in many locations Works well in small currents	Extra power to rotate the jets Difficult to deploy in finger berths Difficult to maintain

[a]Pattern Angle $\theta_{cr} = -4.64\beta + 612\beta^2$

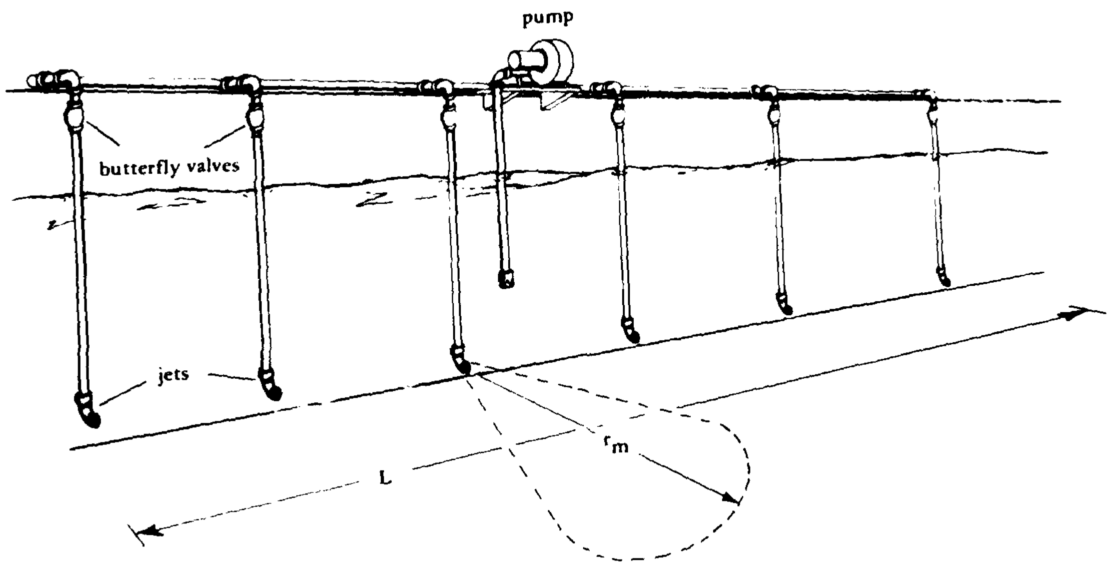


Figure 1. Sketch of a linear scour jet array system with a length L and scour radius r_m. (A typical scour jet array has a length of 300 feet and a scour radius of 75 feet.)

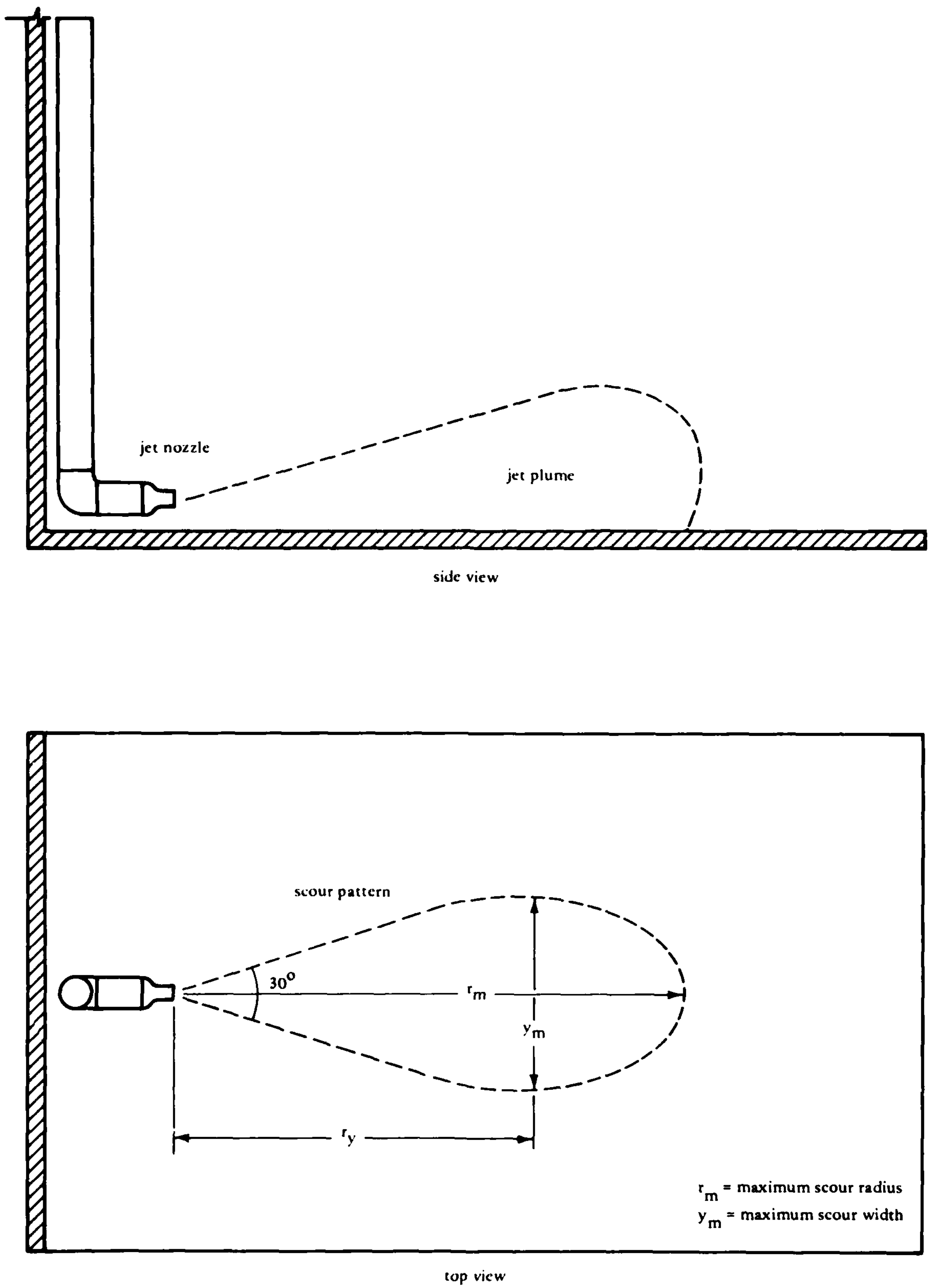


Figure 2. Sketch of ideal jet plume and scour pattern boundaries for horizontal bottom-mounted jet.

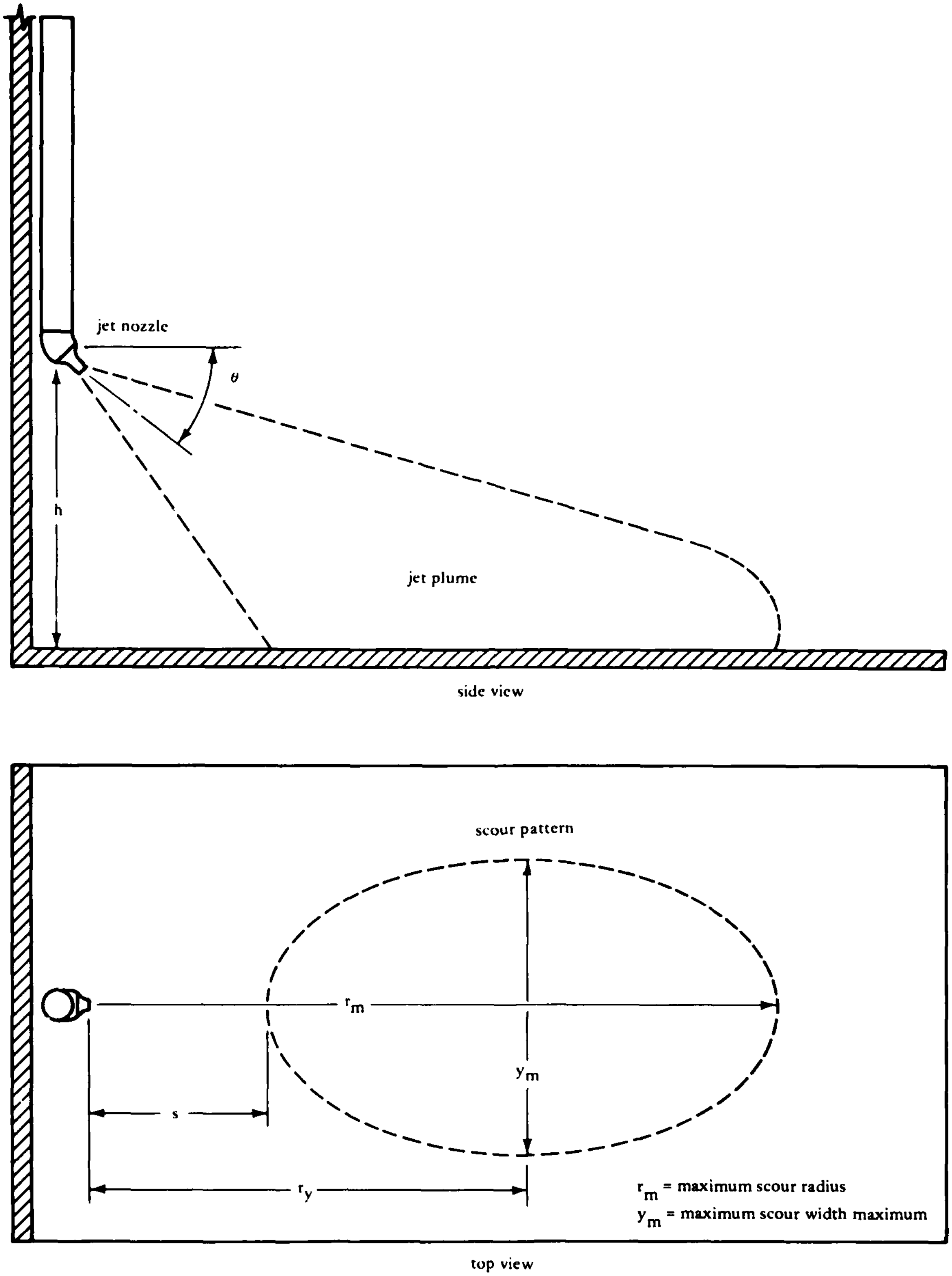


Figure 3. Sketch of ideal jet plume and scour pattern boundaries for angled, elevated jet.

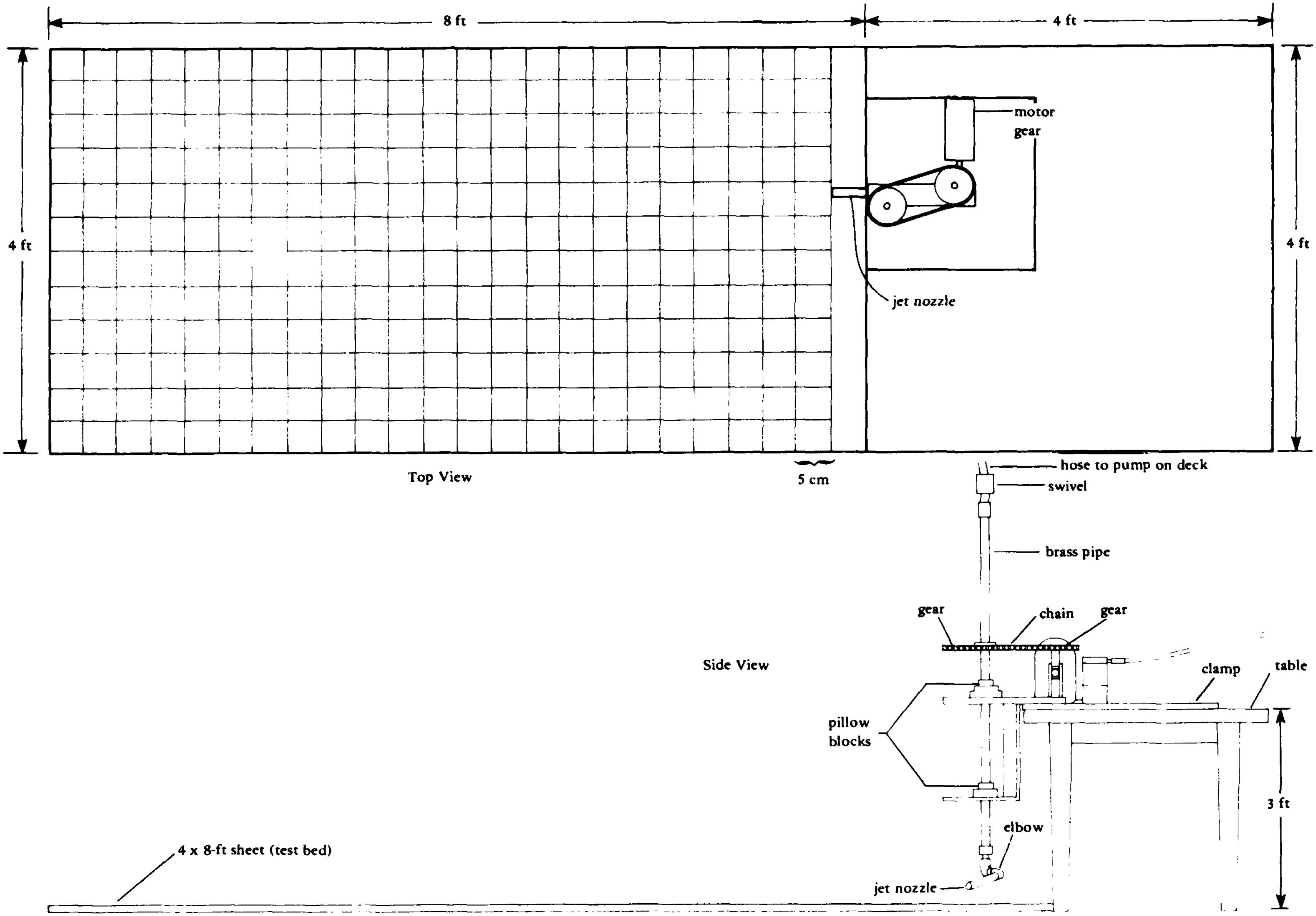


Figure 4. Motor, jet assembly, and test bed.

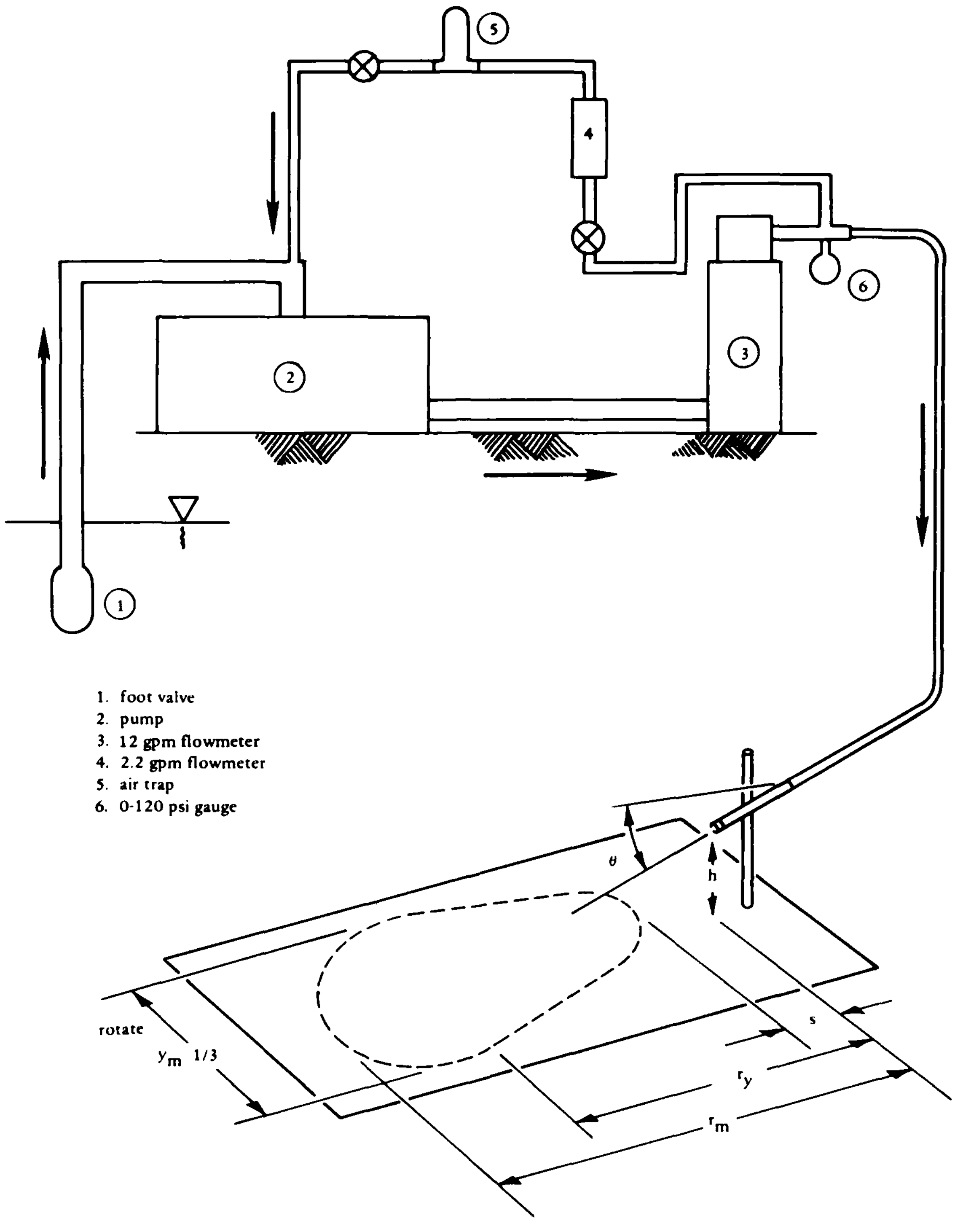


Figure 5. Pump with flowmeter manifold.

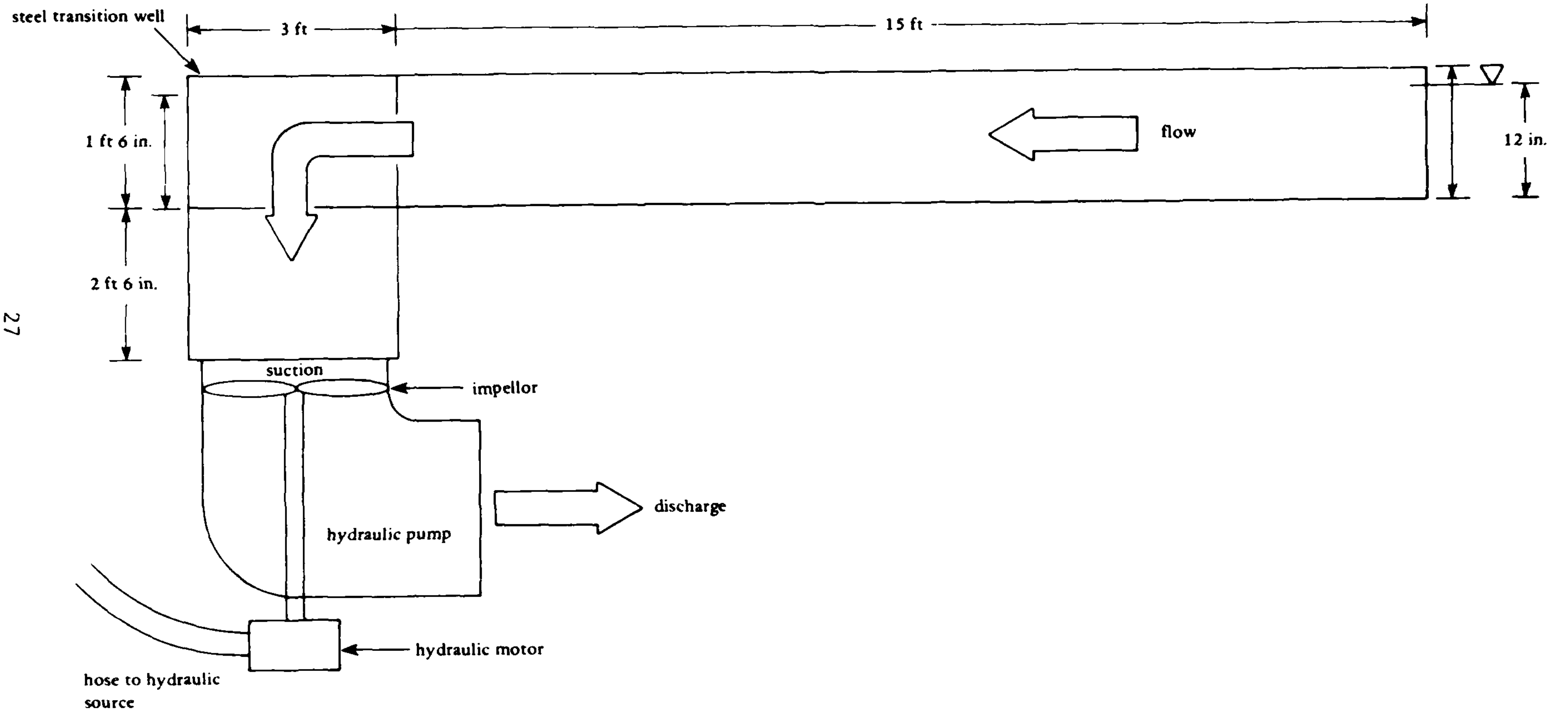


Figure 6. Hydraulic pump and flow channel.

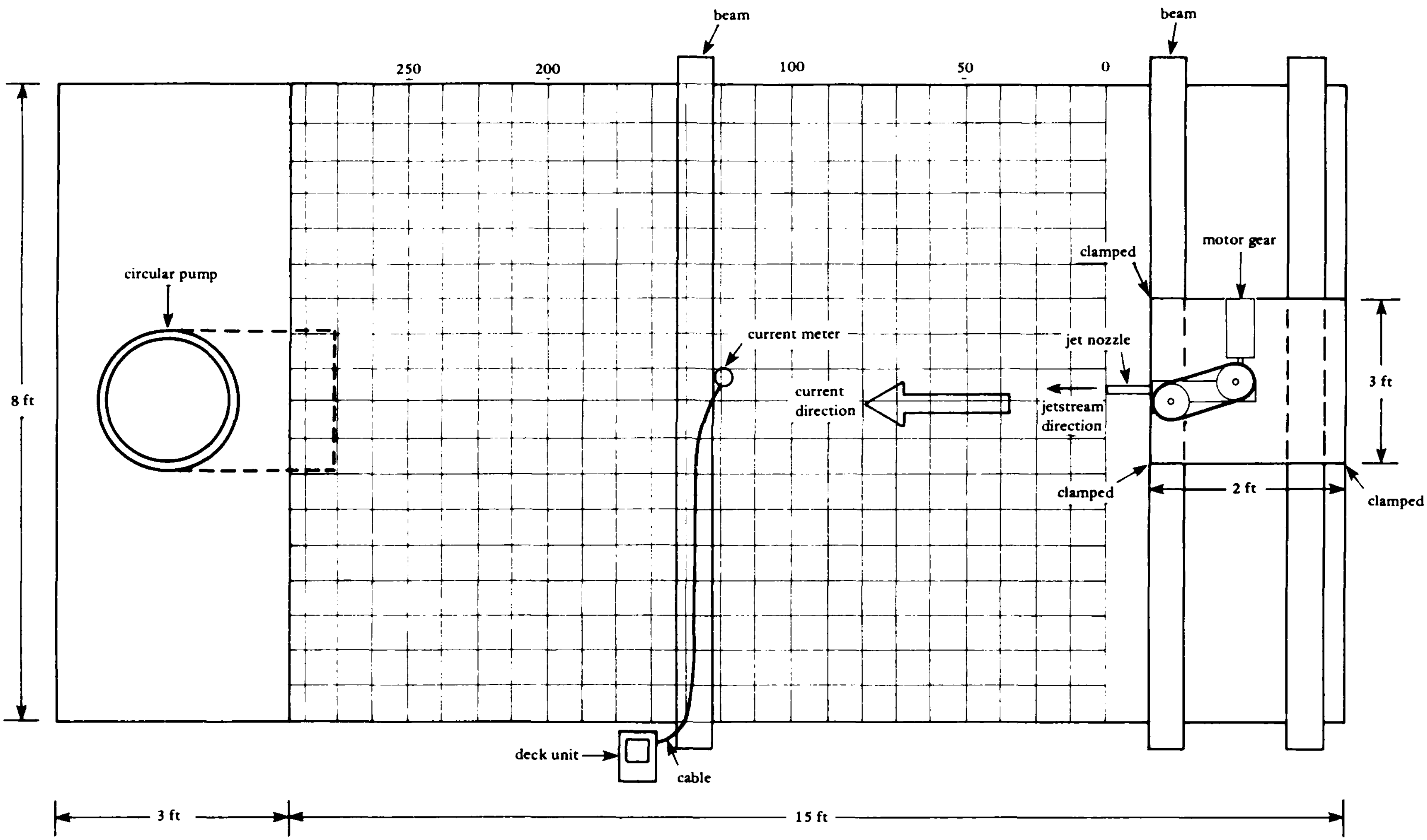


Figure 7. Coflow schematic (jetstream in the same direction as the current).

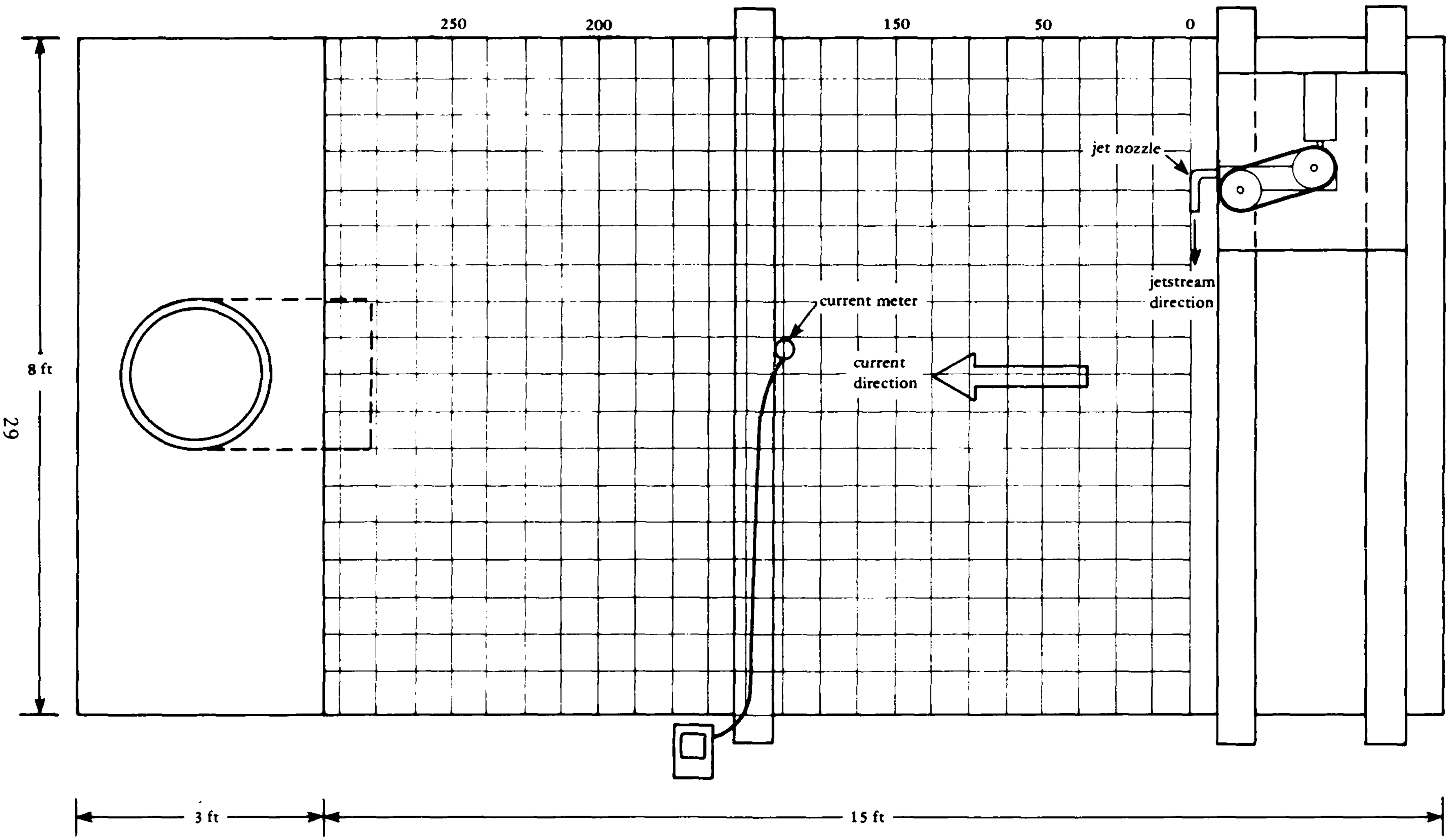


Figure 8. Crossflow schematic (jetstream perpendicular to the current).

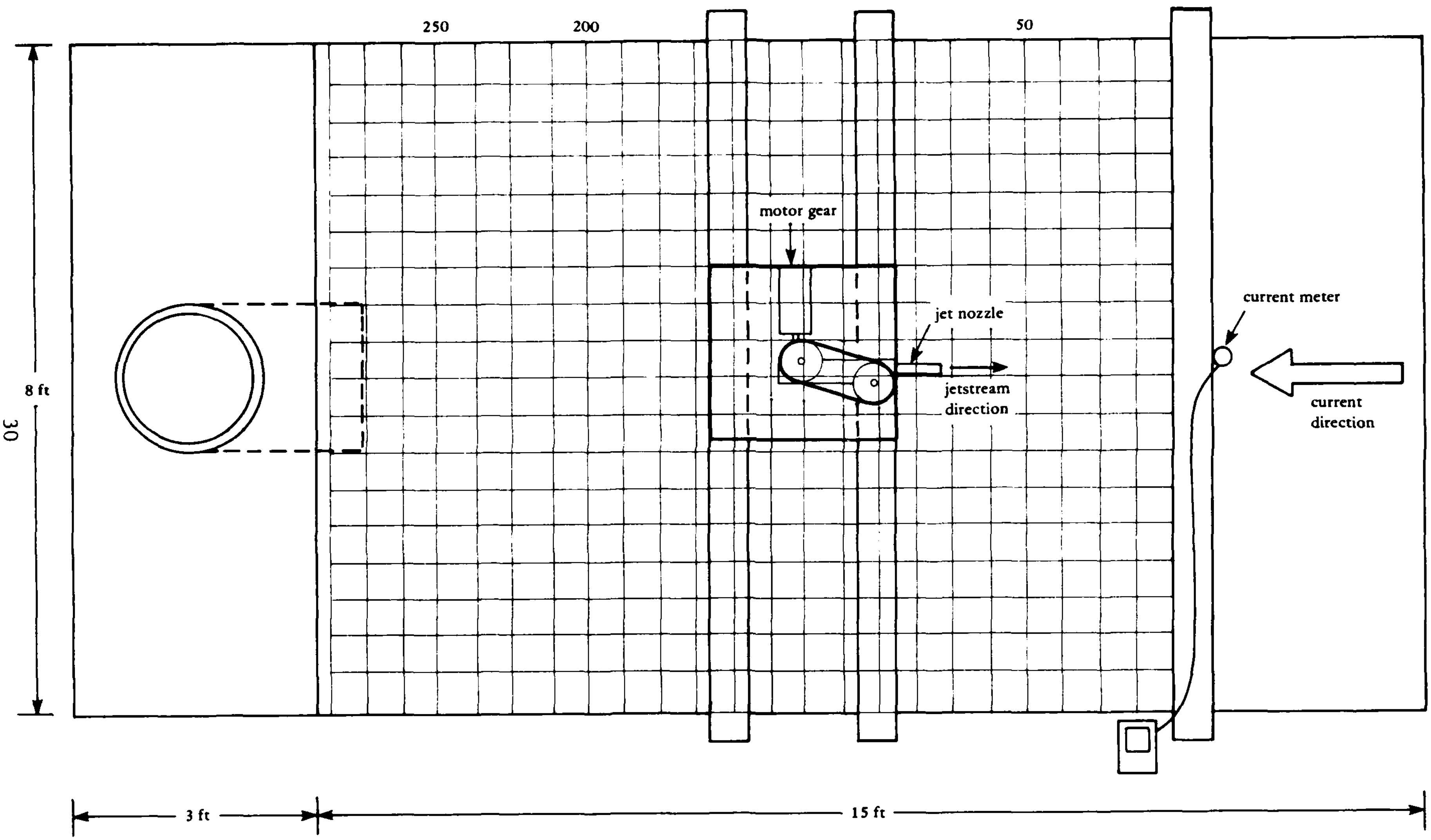


Figure 9. Counterflow schematic (jetstream opposing the current).

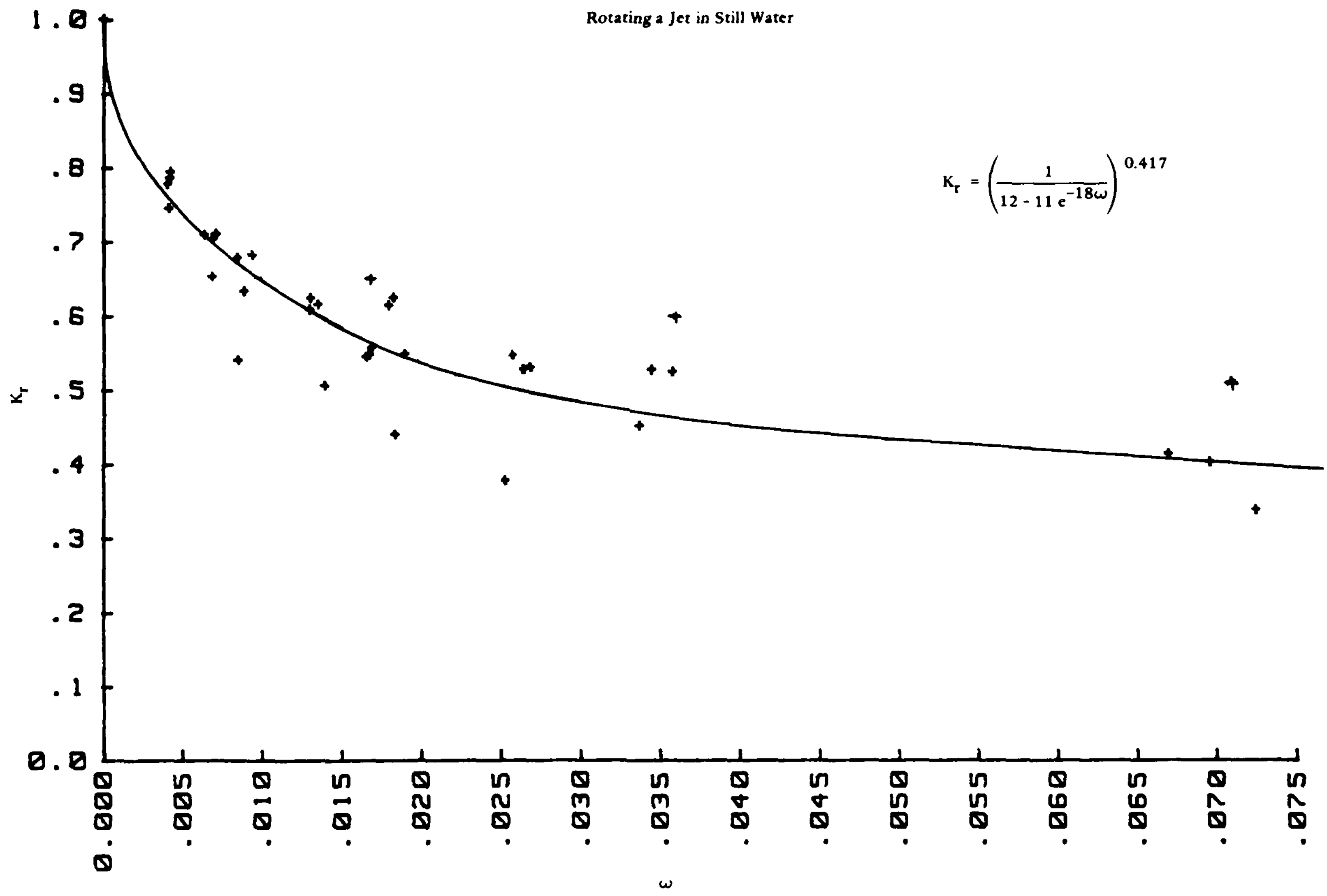


Figure 10. Equation and graph for predicting scour radius given a jet (discharge rate, diameter, and rotation rate); no current.

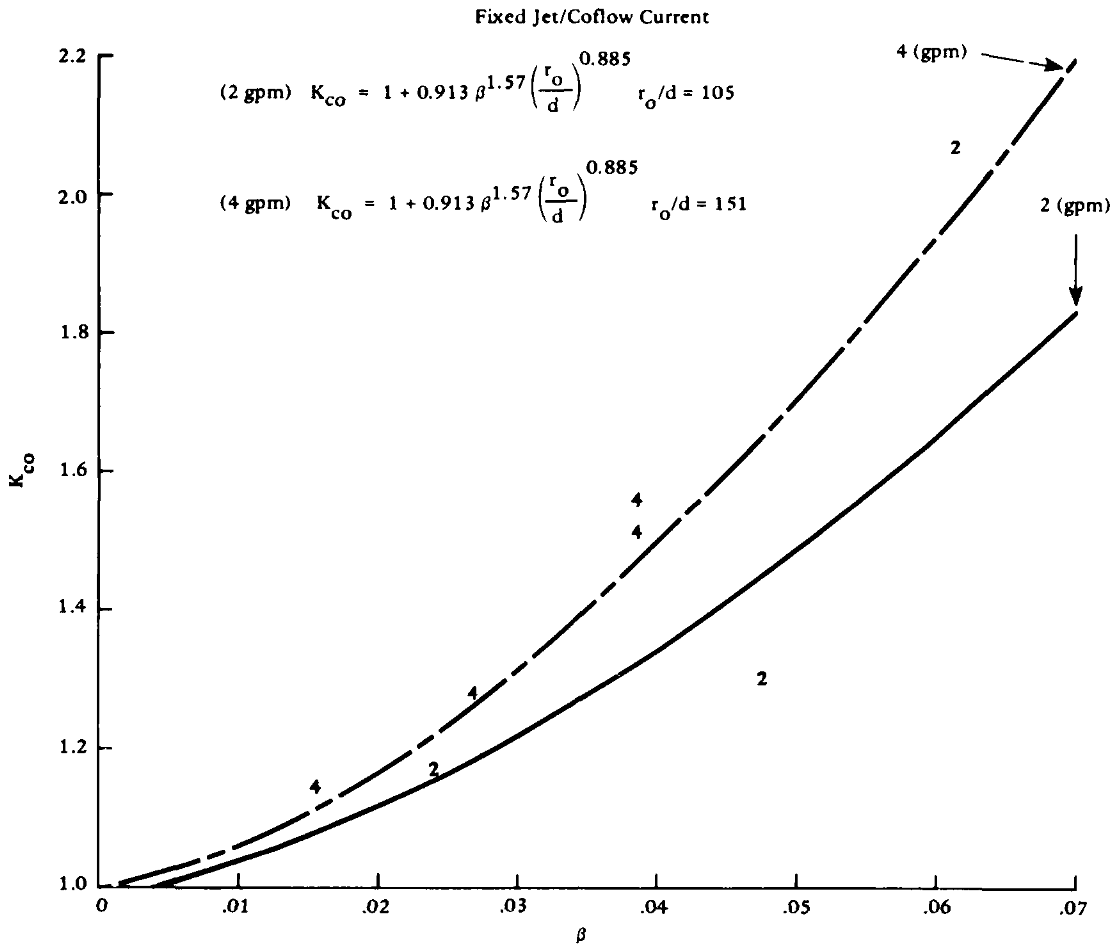


Figure 11. Equation and graph for predicting scour radius given a jet (discharge rate and diameter) and mean current velocity.

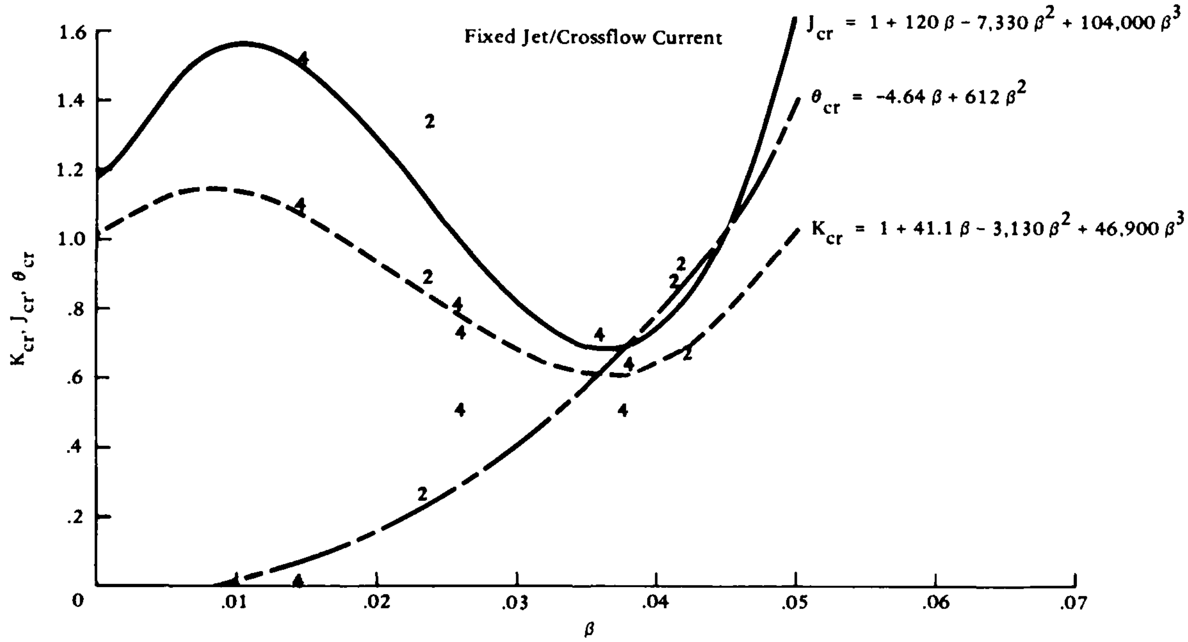


Figure 12. Equations and graph for predicting scour (radius, width, and angle) given a jet (discharge rate and diameter) and mean current velocity.

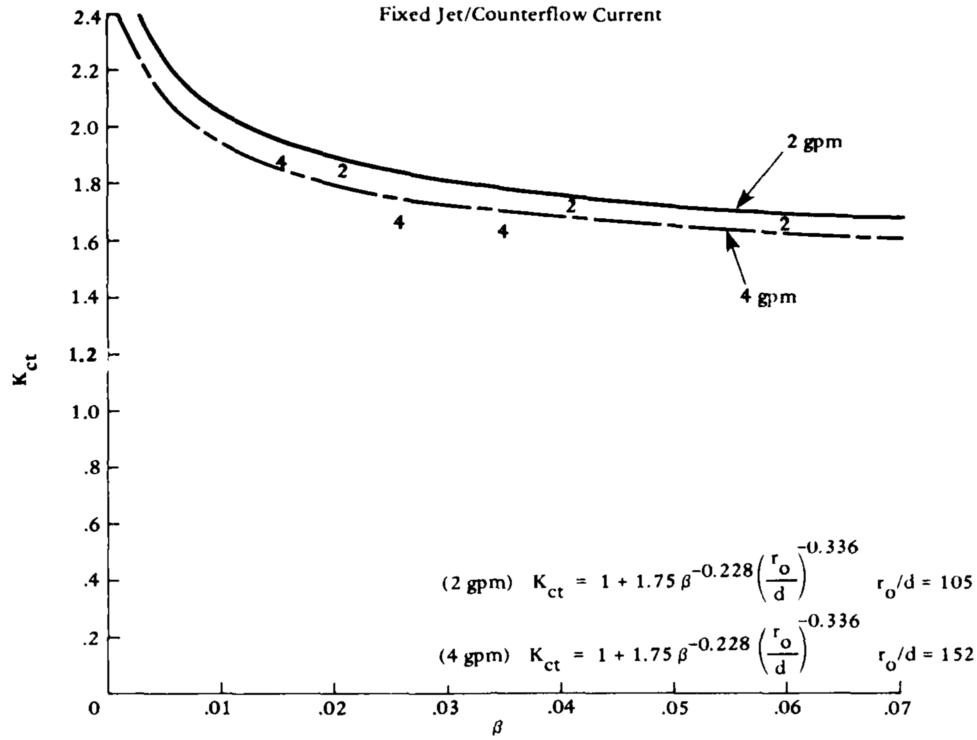


Figure 13. Equations and graph for predicting scour radius given a jet (discharge rate and diameter) and a mean current velocity.

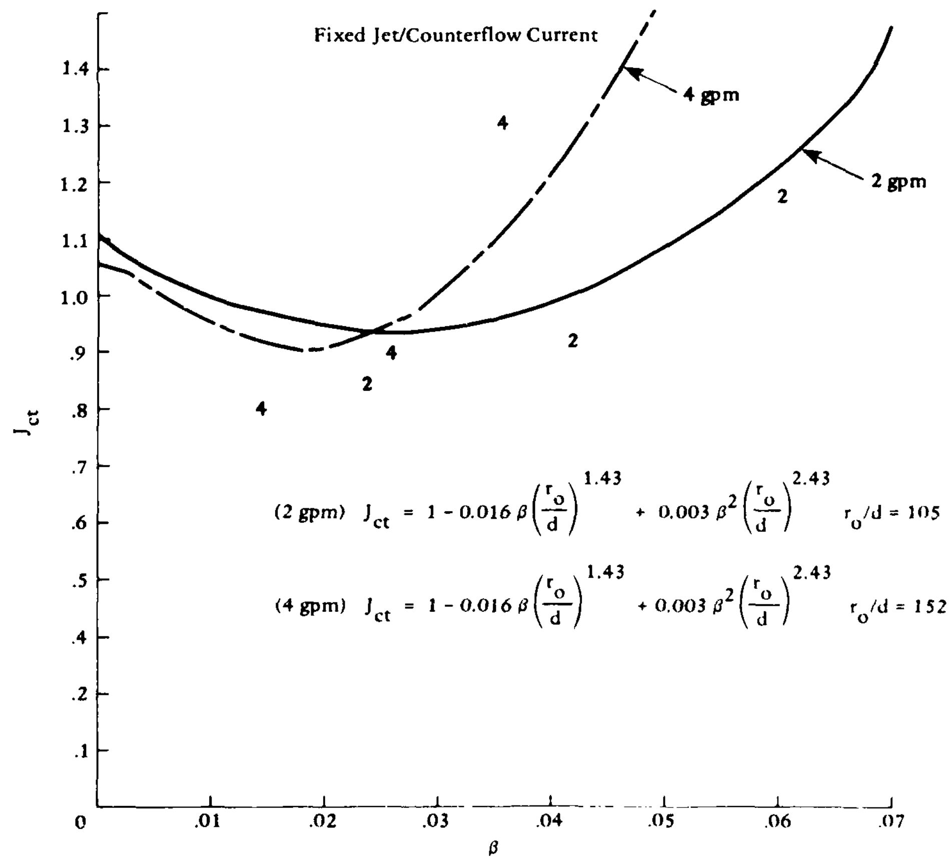


Figure 14. Equations and graph for predicting scour width given a jet (discharge rate and diameter) and a mean current velocity.

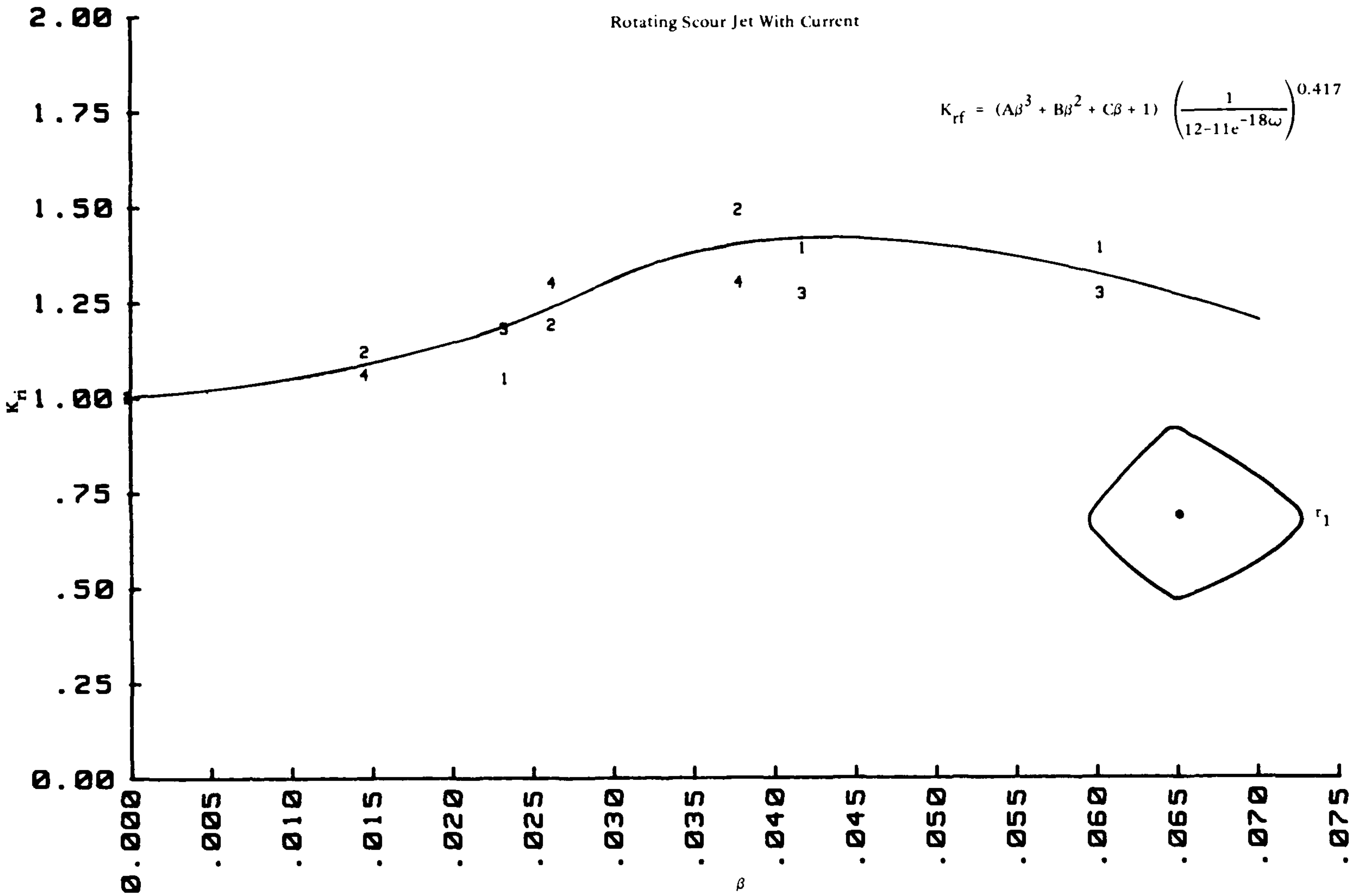


Figure 15. Equation and graph for predicting scour radius coordinate r_1 given a jet (discharge rate, rotation rate, and diameter) and a mean current velocity.

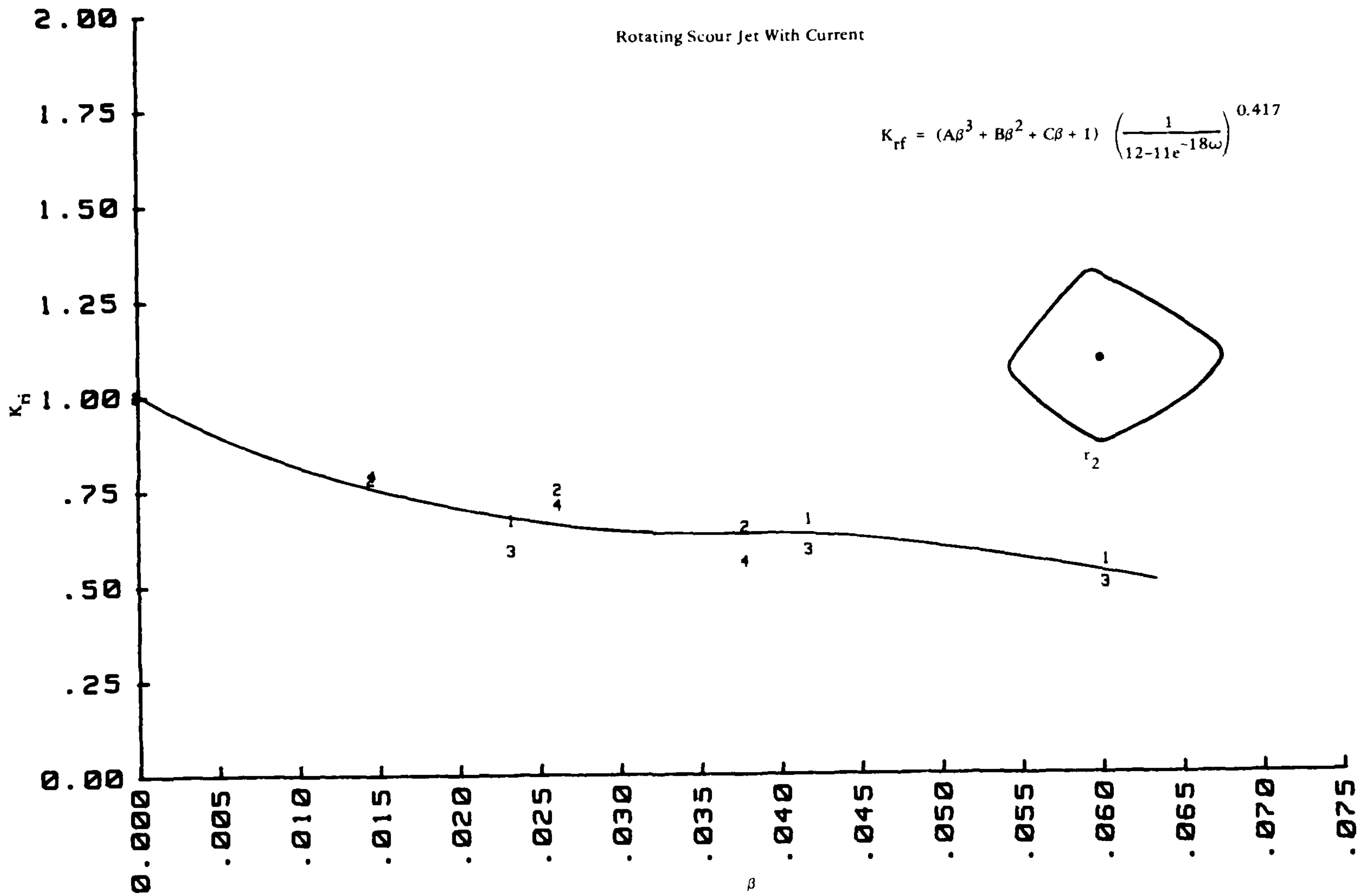


Figure 16. Equation and graph for predicting scour radius coordinate r_2 given a jet (discharge rate, rotation rate, and diameter) and a mean current velocity.

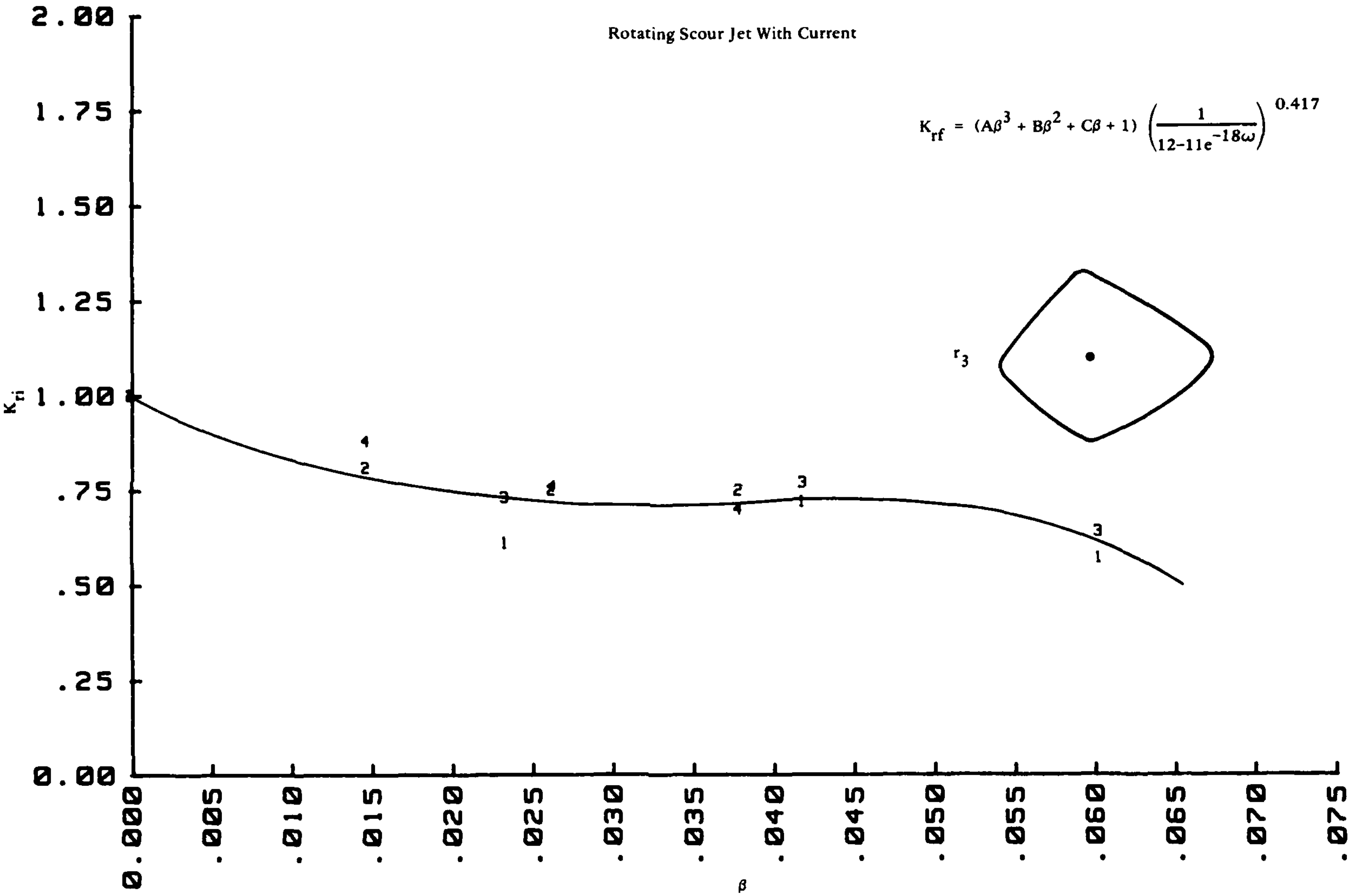


Figure 17. Equation and graph for predicting scour radius coordinate r_3 given a jet (discharge rate, rotation rate, and diameter) and a mean current velocity.

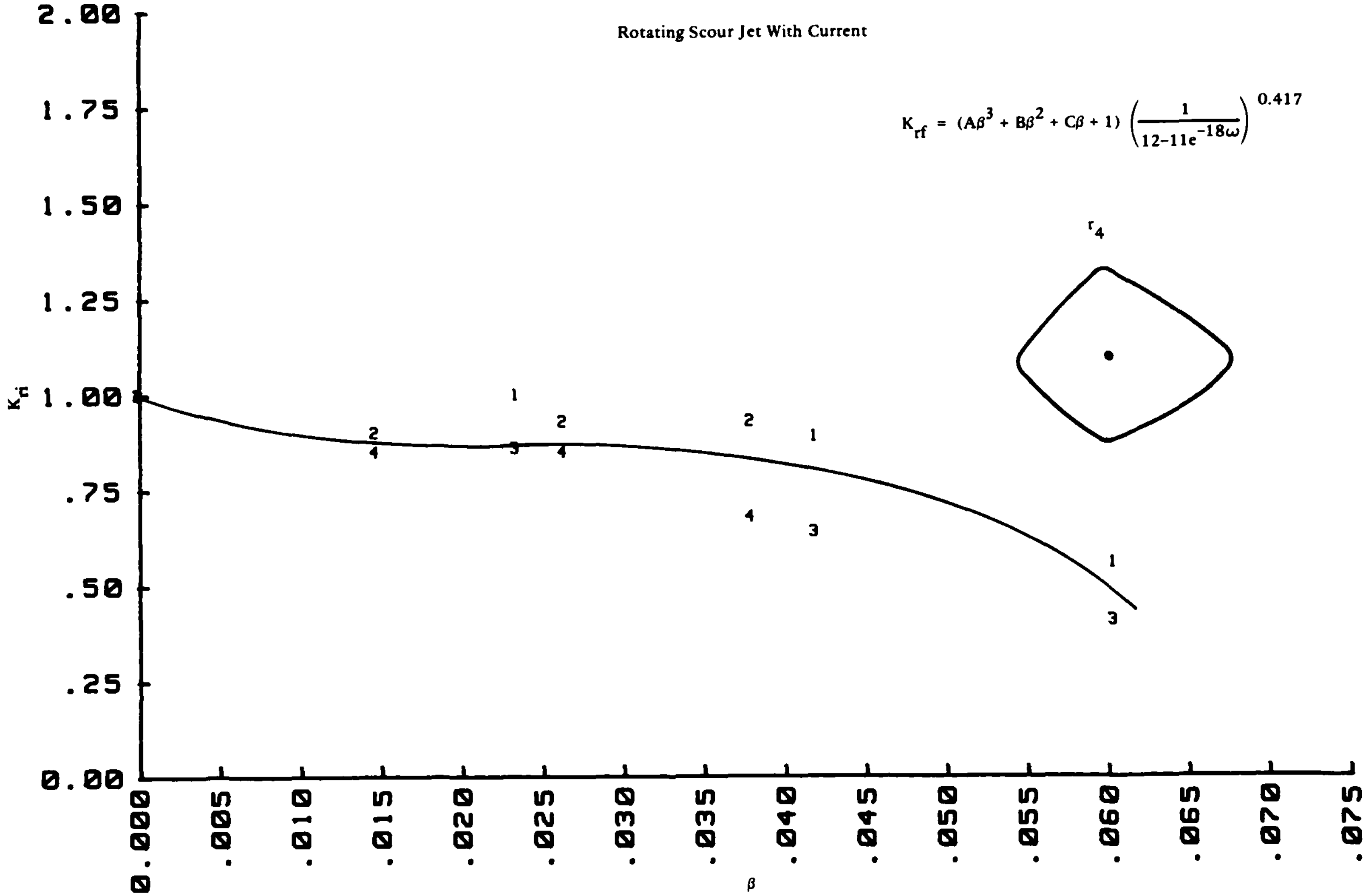


Figure 18. Equation and graph for predicting scour radius coordinate r_4 given a jet (discharge rate, rotation rate, and diameter) and a mean current velocity.

Appendix A

EQUATIONS DESCRIBING SCOUR PATTERN (WIDTH AND RADIUS) DERIVED BY VAN DORN, BAILARD, AND CAMPERMAN

Van Dorn et al. (Ref 1) used a thin layer of diatomaceous earth to indicate a shear stress level of 0.1 Pa (1.45×10^{-5} psi). These results were generalized in the form of an equation for maximum scour radius:

$$\left(\frac{r_{m_o}}{d}\right)^{2.4} = \frac{120\ \rho\ u_o^2}{\tau\ R_e^{0.4}} \qquad \text{(A-1)}$$

where τ = induced shear stress on the bed

u_o = jet discharge velocity

d = jet diameter

ρ = fluid density

R_e = Reynolds number for the jet, $(U_o d/v)$

v = fluid kinematic viscosity

r_{m_o} = maximum scour radius in still fluid

Referring to Figure 2, the maximum width, y_{m_o}, of the scour pattern equals $r_{m_o}/3$ and is located a distance of 0.67 r_{m_o} from the jet nozzle. Bailard and Camperman (Ref 3) showed that the jet scour pattern is also a function of the jet height from the bottom, h, and the jet angle relative to the horizontal, Θ. For a raised, angled jet (Figure 3), the maximum scour distance is:

$$\left(\frac{r_{m_o}}{d}\right) = \left(\frac{\tau \, R_e^{0.4} \times 10^4}{C_o \, \rho \, u_o^2}\right)^{C_1} \qquad \text{(A-2)}$$

$$\text{where } C_o = 10^{(-C_2/C_1)} \qquad \text{(A-3)}$$

$$C_1 = 0.0533 \sin (5.59 \, \theta) - 0.385 + (-0.0201 + 0.00593 \, \theta^{0.356}) \, (h/d) \qquad \text{(A-4)}$$

$$C_2 = 2.442 + 0.0108 \, (h/d) - 1.266 \times 10^{-4} \, (h/d)^2 - 0.0118 \, \theta - 9.33 \times 10^{-5} \, \theta^2 \qquad \text{(A-5)}$$

Laboratory tests have shown that small jet angles (just below horizontal) and low heights (just above sediment surface) are most effective in producing scour over a significant distance.

Referring to Figure 3, a new variable, S, described the horizontal distance from the jet to the point initiating scour. Despite considerable effort, analytic expressions such as Equations A-1 and A-2 could not be derived for predicting pattern width, y_m, maximum radius width, r_y, nor the distance to initial scour, S. Instead, graphical solutions were required.

Appendix B

SCOUR DATA FROM EXPERIMENTAL INVESTIGATION - PART I

Recorder No.	Recorder Date	Start Time	Finish Time	θ (deg)	Height (cm)	ω' (rpm)	Q (gpm)	r (cm)	Comments/ Observations
1	5/8/84	1357	1407	0	0	2	2	50-55	Q = 2.25
2	5/8/84	1413	1423	0	0	1	2	60-65	
3	5/8/84	1428	1438	0	0	0.5	2	65-70	
4	5/8/84	1440	1450	0	0	0	2	88-95	
5	5/8/84	1458	1508	0	0	2	5	88-95	
6	5/8/84	1514	1524	0	0	1	5	100-110	
7	5/8/84	1526	1536	0	0	0.5	5	120-125	
8	5/8/84	1538	1548	0	0	0	5	170-175	
9	5/8/84	1608	1618	0	0	2	8	115	
10	5/8/84	1621	1631	0	0	1	8	140-145	
11	5/8/84	1634	1644	0	0	0.5	8	160-170	
12	5/8/84	1646	1650	0	0	0	8	210	spotted
13	5/9/84	1025	1035	15	15	2	2	23-33	
14	5/9/84	1042	1052	15	15	1	2	40-47	first 25 cm no scour
15	5/9/84	1101	1111	15	15	0.5	2	50-52	
16	5/9/84	1112	1122	15	15	0	2	83	
17	5/9/84	1127	1137	15	15	2	5	85-90	
18	5/9/84	1145	1155	15	15	1	5	98-99	
19	5/9/84	1204	1214	15	15	0.5	5	110-115	
20	5/9/84	1215	1225	15	15	0	5	155-165	spotted pattern
21	5/9/84	1328	1338	15	15	2	8	115-118	
22	5/9/84	1347	1357	15	15	1	8	140-145	
23	5/9/84	1402	1412	15	15	0.5	8	160-165	
24	5/9/84	1413	1423	15	15	0	8	220	spotted

θ = Jet Angle w. horizontal
ω = Rotation Speed
Q = Flowrate
D = Scour Distance
C = Current Speed

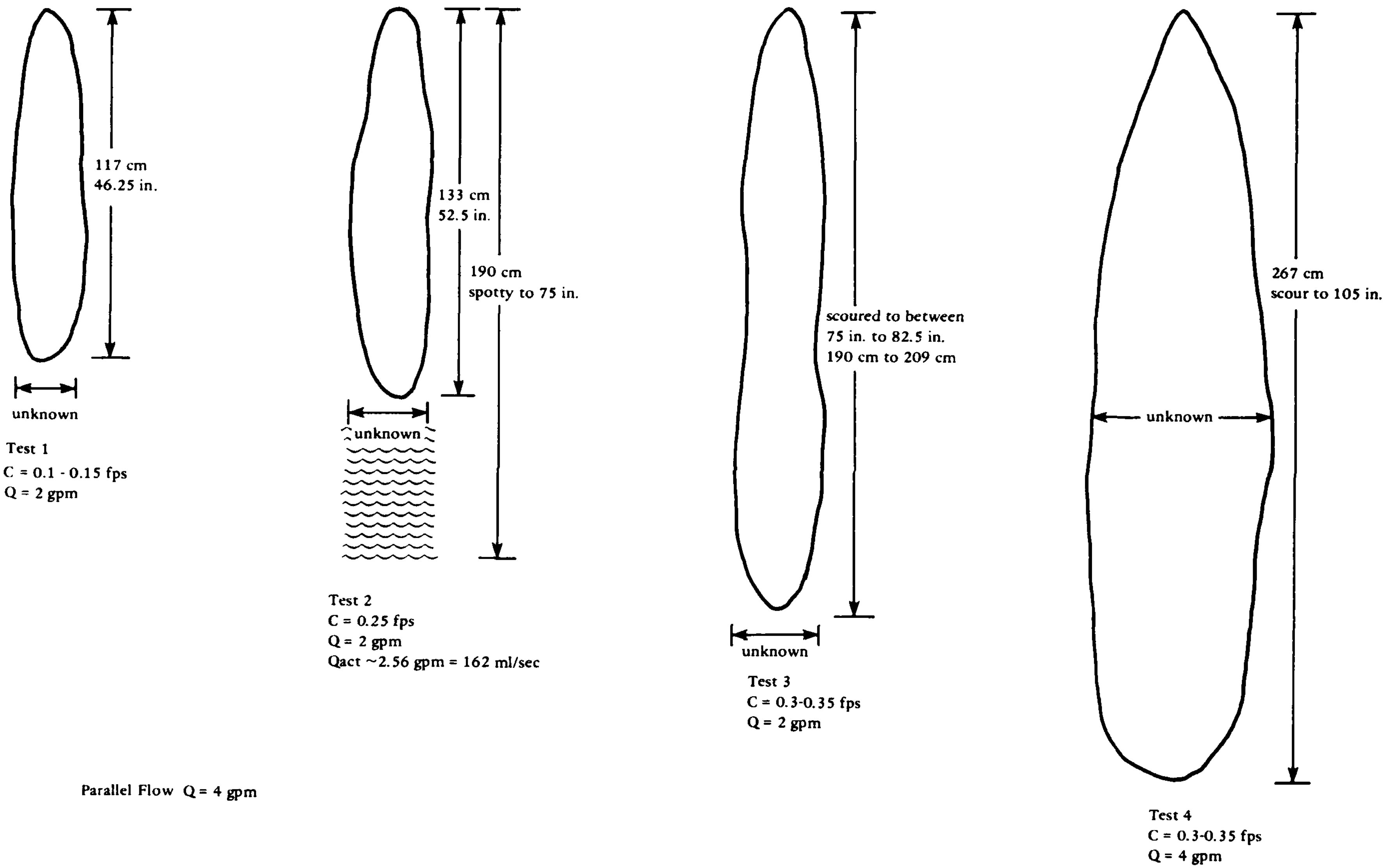
(continued)

Recorder		Start Time	Finish Time	θ (deg)	Height (cm)	ω' (rpm)	Q (gpm)	r (cm)	Comments/ Observations
No.	Date								
25	5/10/84	0918	0928	5	15	2	2		spotty at 32 no scour
26	5/10/84	0935	0945	5	15	1	2	30-40	spotted
27	5/10/84	0959	1009	5	15	0.5	2	35-50	spotted
28	5/10/84	1010	1020	5	15	0	2	75-80	
29	5/10/84	1023	1033	5	15	2	5	68	
30	5/10/84	1038	1048	5	15	1	5	87-95	
31	5/10/84	1053	1103	5	15	0.5	5	110-125	
32	5/10/84	1104	1114	5	15	0	5	180	spotted
33	5/10/84	1129	1139	5	15	2	8	105-115	
34	5/10/84	1144	1154	5	15	1	8	135	
35	5/10/84	1159	1209	5	5	0.5	8	187-210	
36	5/10/84	1210	1220	5	15	0	8	220	
*Scour began at 30 cm for all tests due to the 5-degree jet angle and 15 cm height									
37	5/10/84	1323	1333	5	7.5	2	2	35-39	
38	5/10/84	1344	1354	5	7.5	1	2	45-52	
39	5/10/84	1359	1409	5	7.5	0.5	2	55-60	
40	5/10/84	1410	1420	5	7.5	0	2	92	
41	5/10/84	1424	1434	5	7.5	2	5	87	
42	5/10/84	1437	1447	5	7.5	1	5	103	
43	5/10/84	1453	1503	5	7.5	0.5	5	117	
44	5/10/84	1504	1514	5	7.5	0	5	165	
45	5/10/84	1539	1549	5	7.5	2	8	120-125	
46	5/10/84	1555	1605	5	7.5	1	8	142-143	
47	5/10/84	1608	1618	5	7.5	0.5	8	165-170	
48	5/10/84	1619	1629	5	7.5	0	8	230	
*Scour began at 17 cm for all tests due to the 5-degree jet angle and 15 cm height									

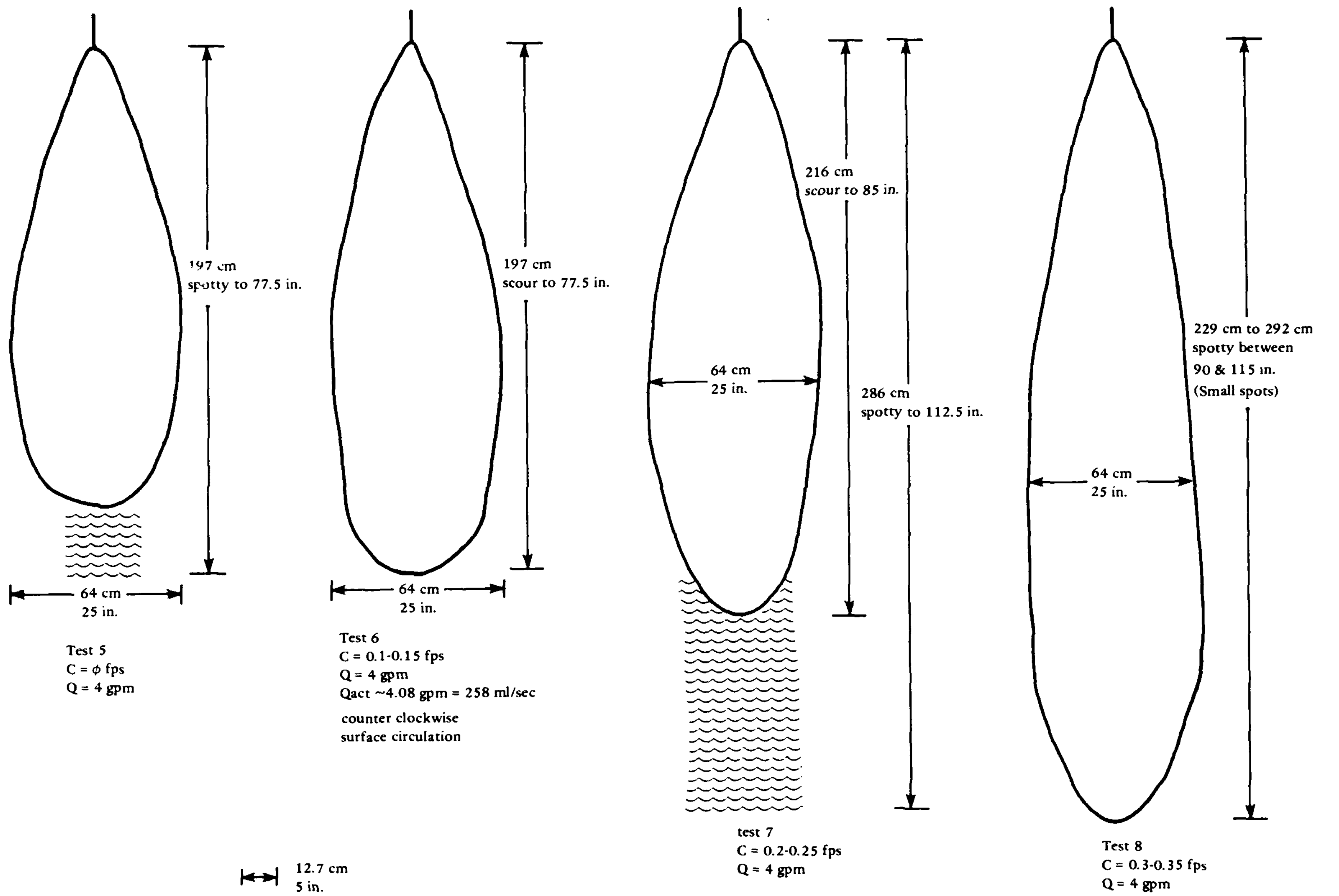
θ = Jet Angle w. horizontal
ω = Rotation Speed
Q = Flowrate
D = Scour Distance
C = Current Speed

Appendix C

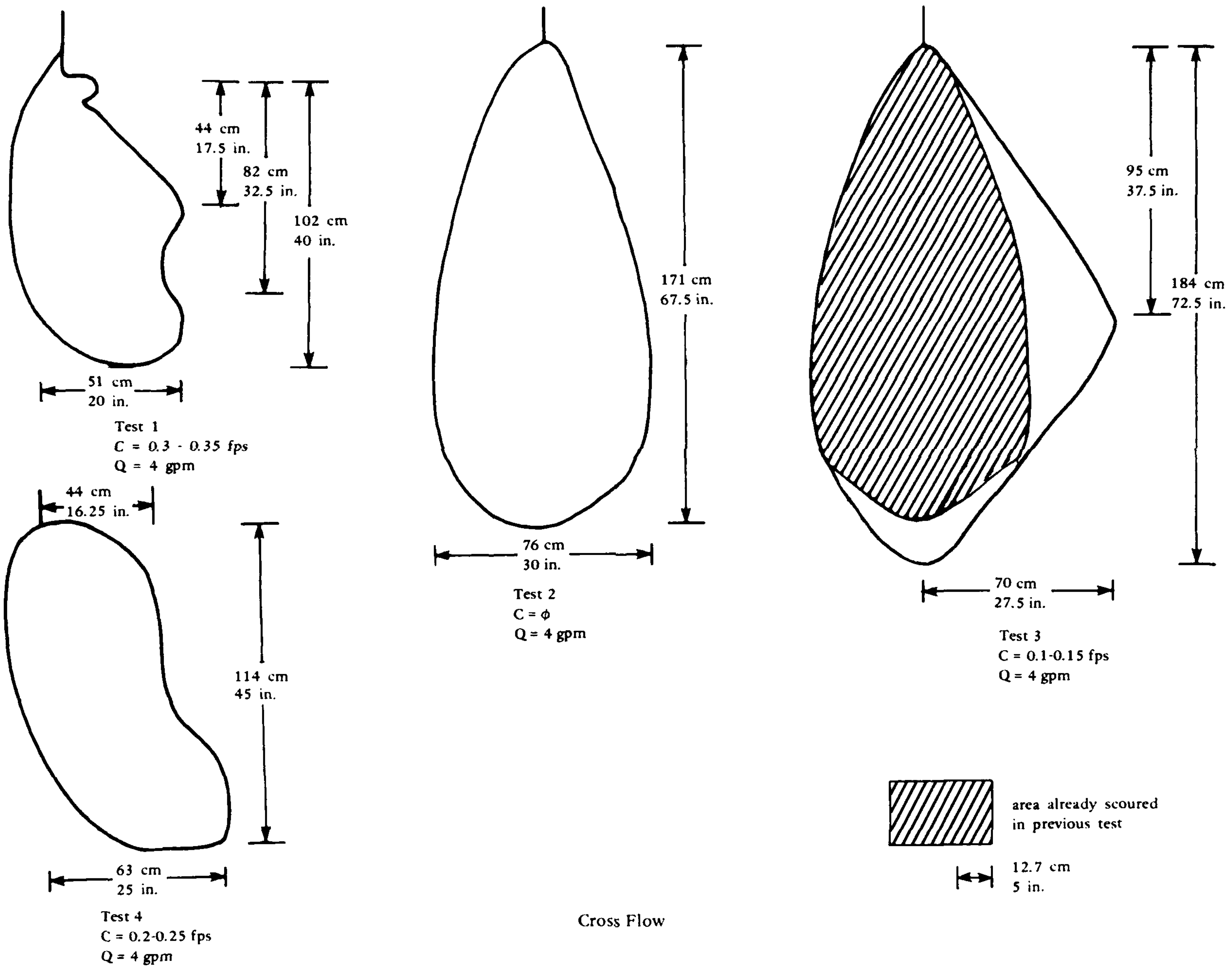
SCOUR PATTERNS FROM EXPERIMENTAL INVESTIGATION - PART II



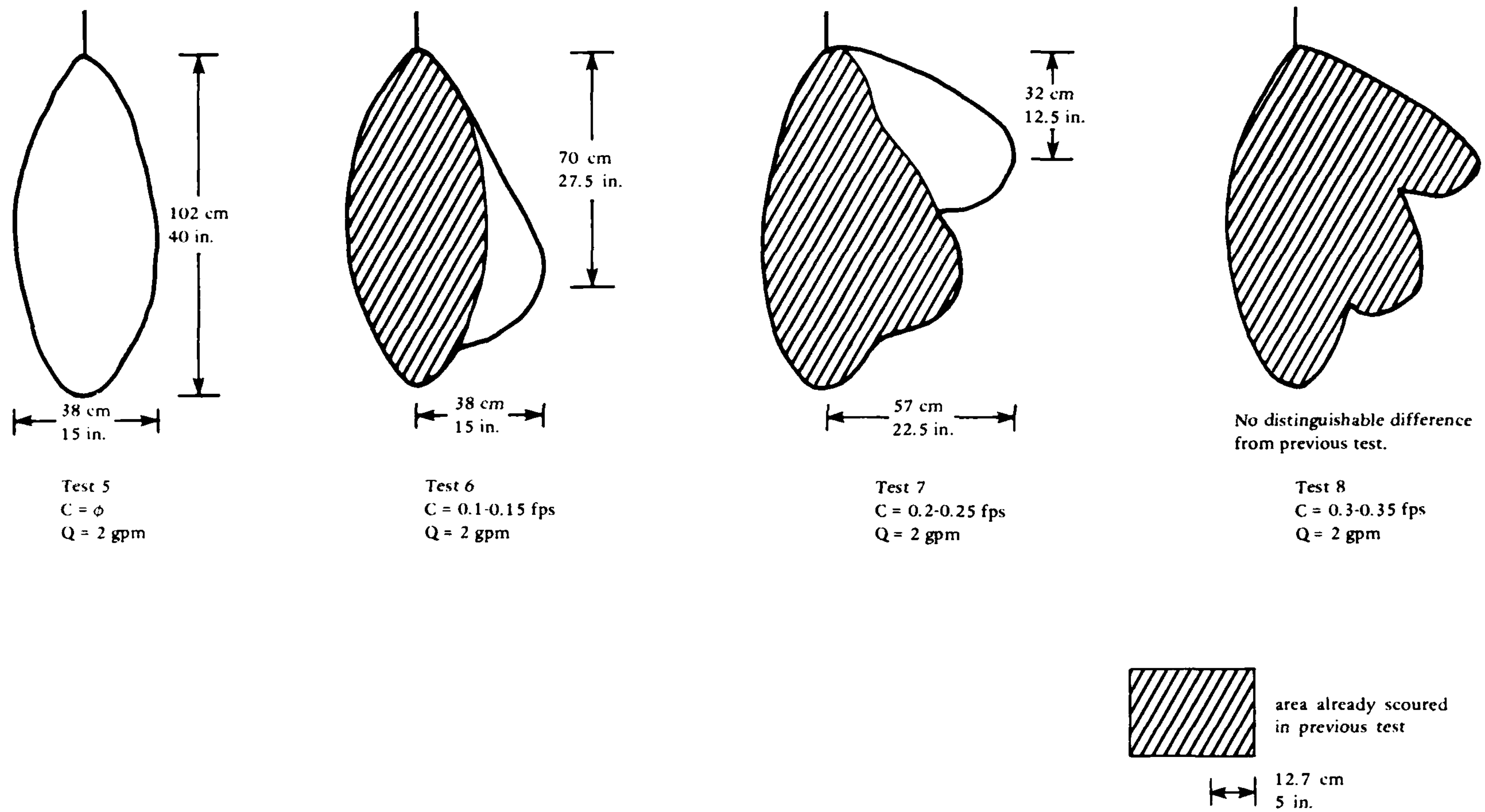
Parallel Flow



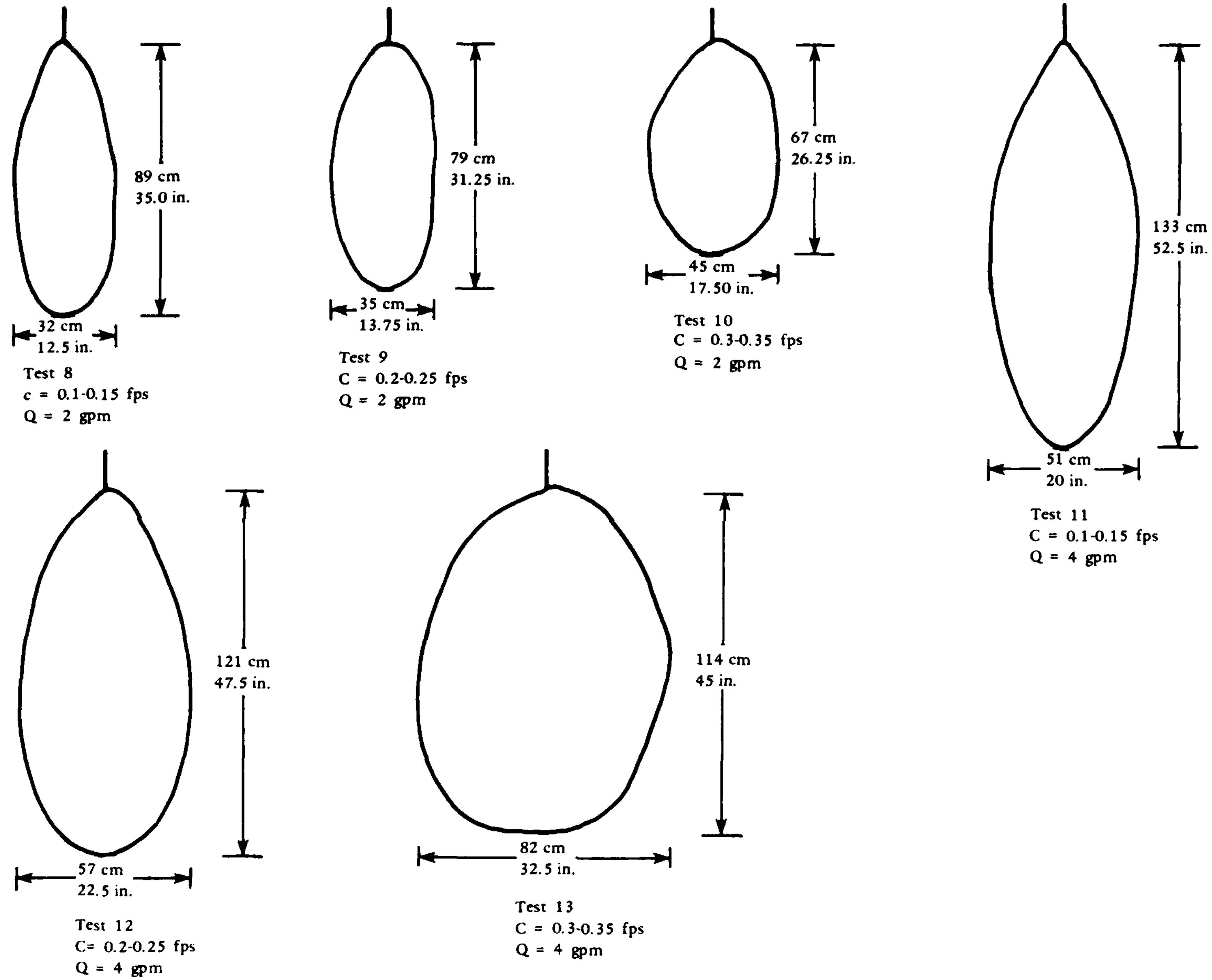
Parallel Flow cont'd


44 cm
17.5 in.
82 cm
32.5 in.
102 cm
40 in.
51 cm
20 in.
Test 1
C = 0.3 - 0.35 fps
Q = 4 gpm
171 cm
67.5 in.
76 cm
30 in.
Test 2
C = ϕ
Q = 4 gpm
95 cm
37.5 in.
184 cm
72.5 in.
70 cm
27.5 in.
Test 3
C = 0.1-0.15 fps
Q = 4 gpm
44 cm
16.25 in.
114 cm
45 in.
63 cm
25 in.
Test 4
C = 0.2-0.25 fps
Q = 4 gpm
area already scoured
in previous test
12.7 cm
5 in.

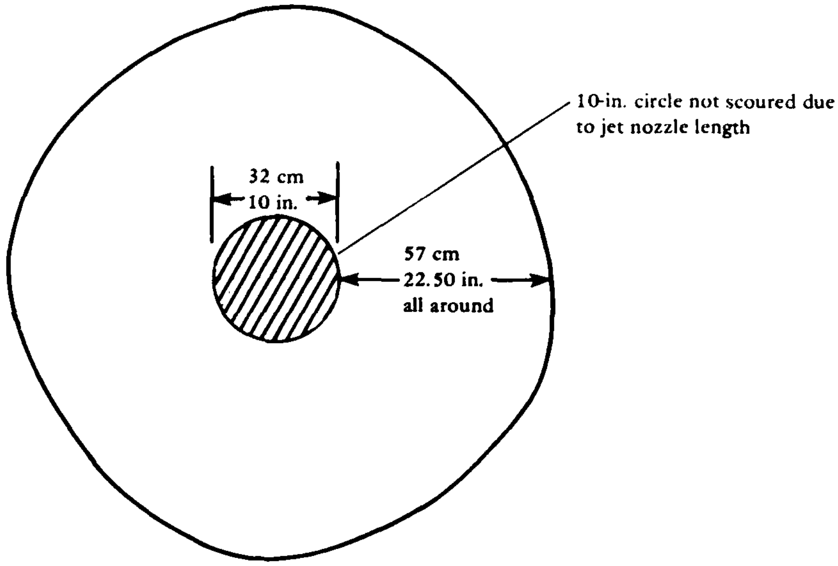
Cross Flow



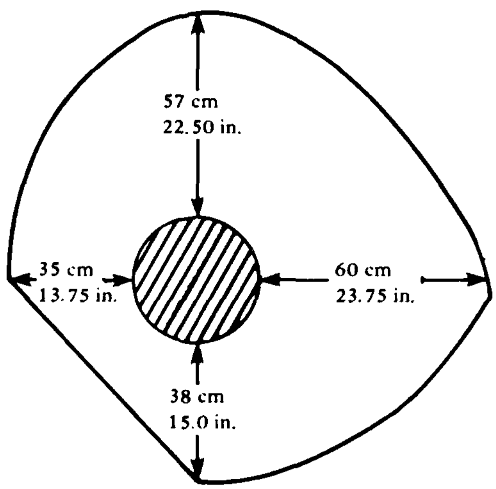
Cross Flow cont'd



Against Current

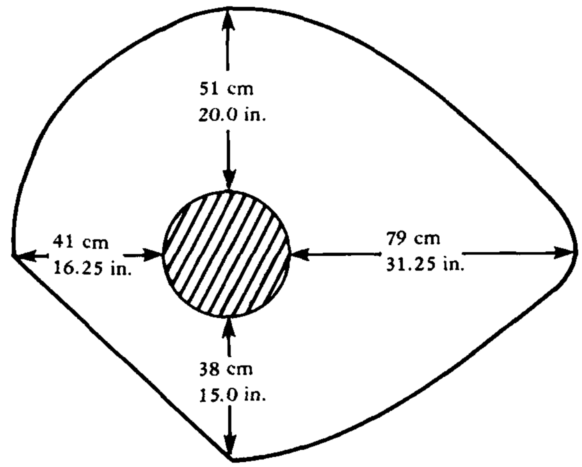


Test 1 - Q = 2 gpm, C = ϕ, w = 67 sec/rev

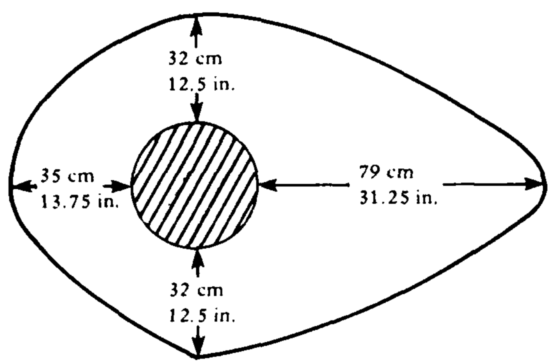


Test 2 - Q = 2 gpm, C = 0.1-0.15, w = 67 sec/rev

Rotating Flow

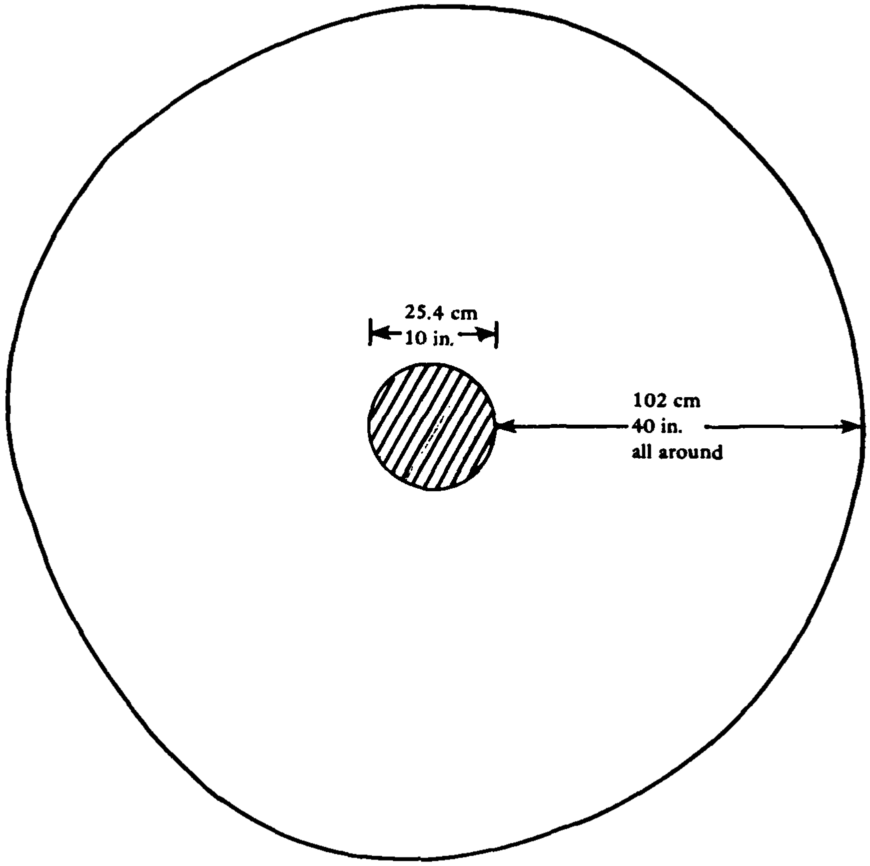


Test 3 - Q = 2 gpm, C = 0.1-0.25 fps, w = 67 sec/rev

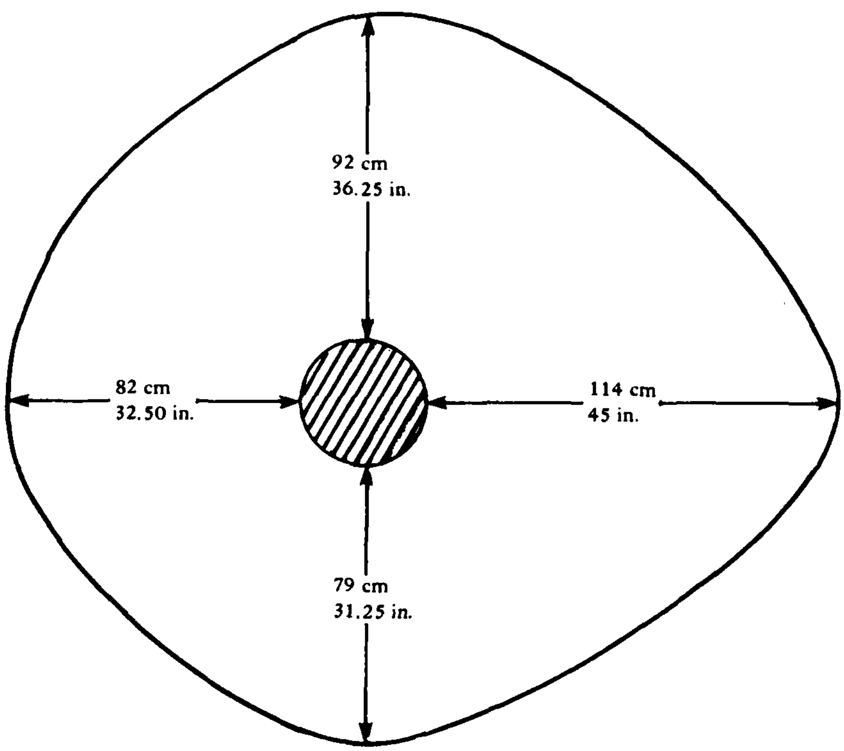


Test 4 - Q = 2 gpm, C = 3-0.35 fps, w = 67 sec/rev

Rotating Flow cont'd

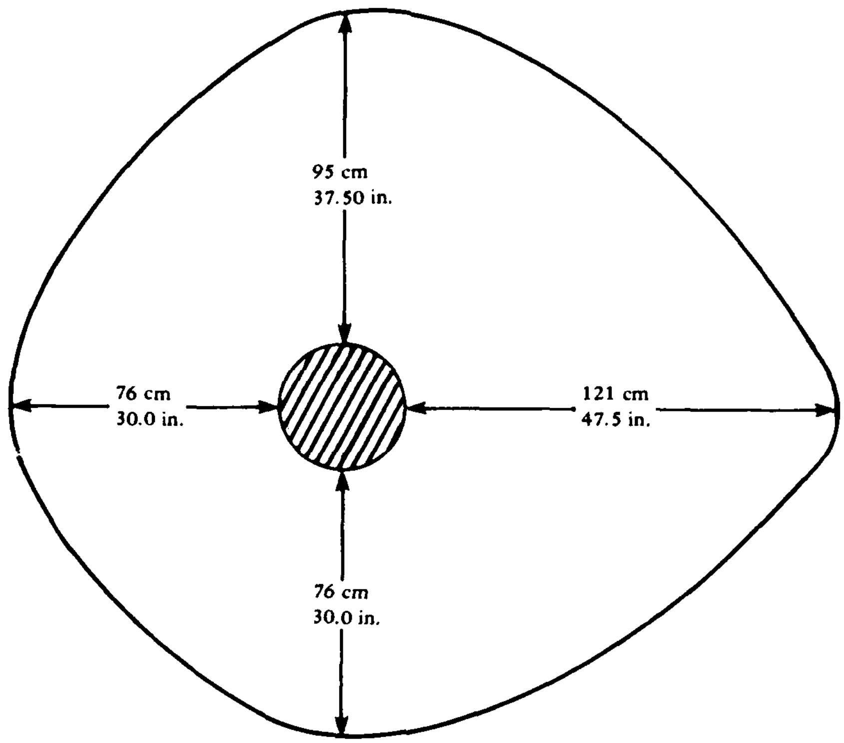


Test 5 - Q = 4 gpm, C = ϕ, w = 67 sec/rev

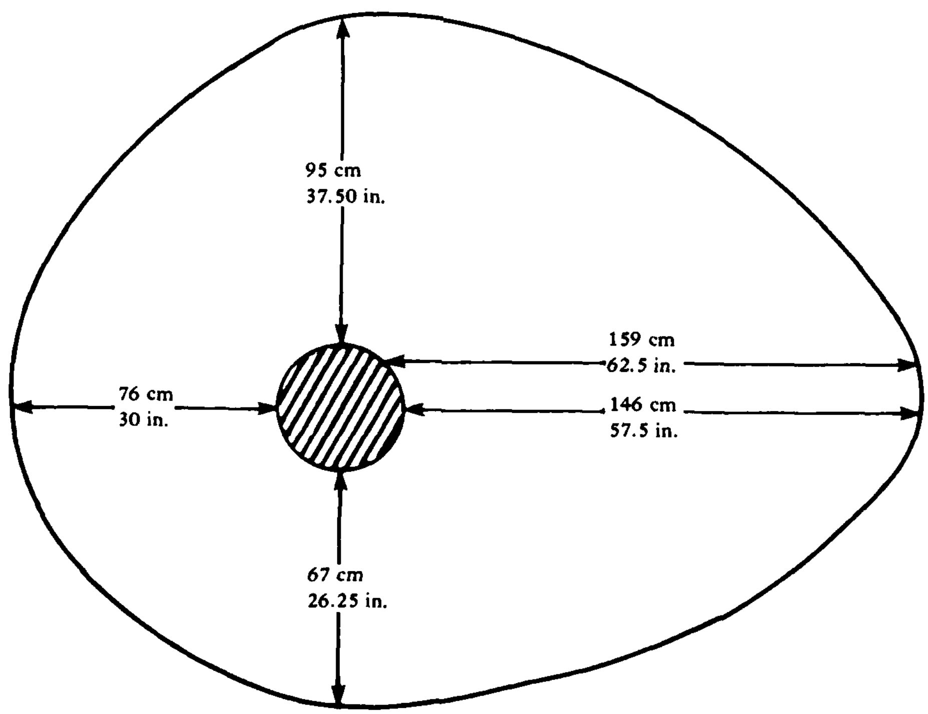


Test 6 - Q = 4 gpm, C = 0.1-0.15, w = 67 sec/rev

Rotating Flow cont'd

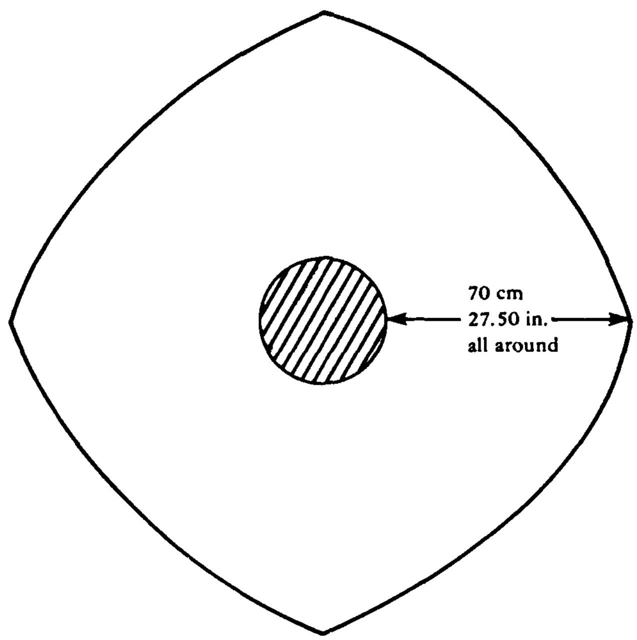


Test 7 - Q = 4 gpm, C = 0.2-0.25 fps, w = 67 sec/rev

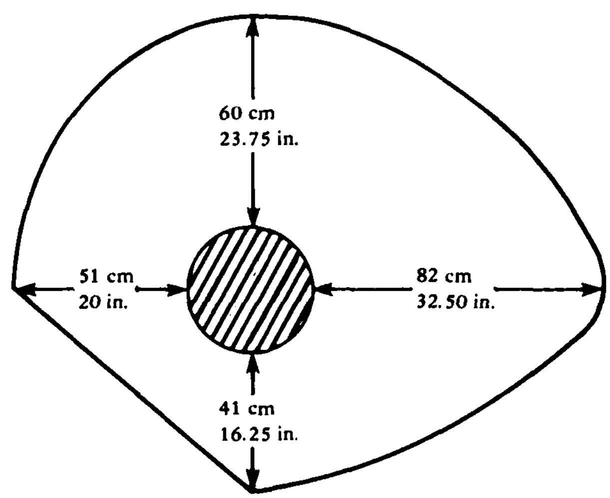


Test 8 - Q = 4 gpm, C = 0.3-0.35 fps, w = 67 sec/rev

Rotating Flow cont'd

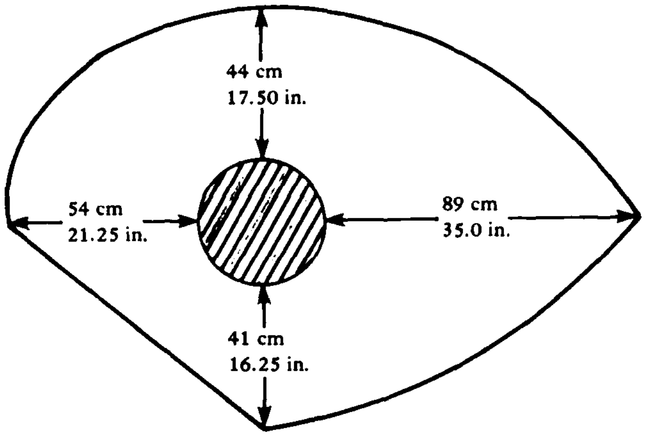


Test 9 - Q = 2 gpm, C = ϕ, w = 114 sec/rev

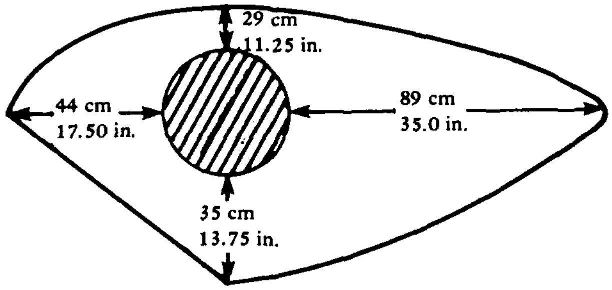


Test 10 - Q = 2 gpm, C = 0.1-0.15, w = 114 sec/rev

Rotating Flow cont'd

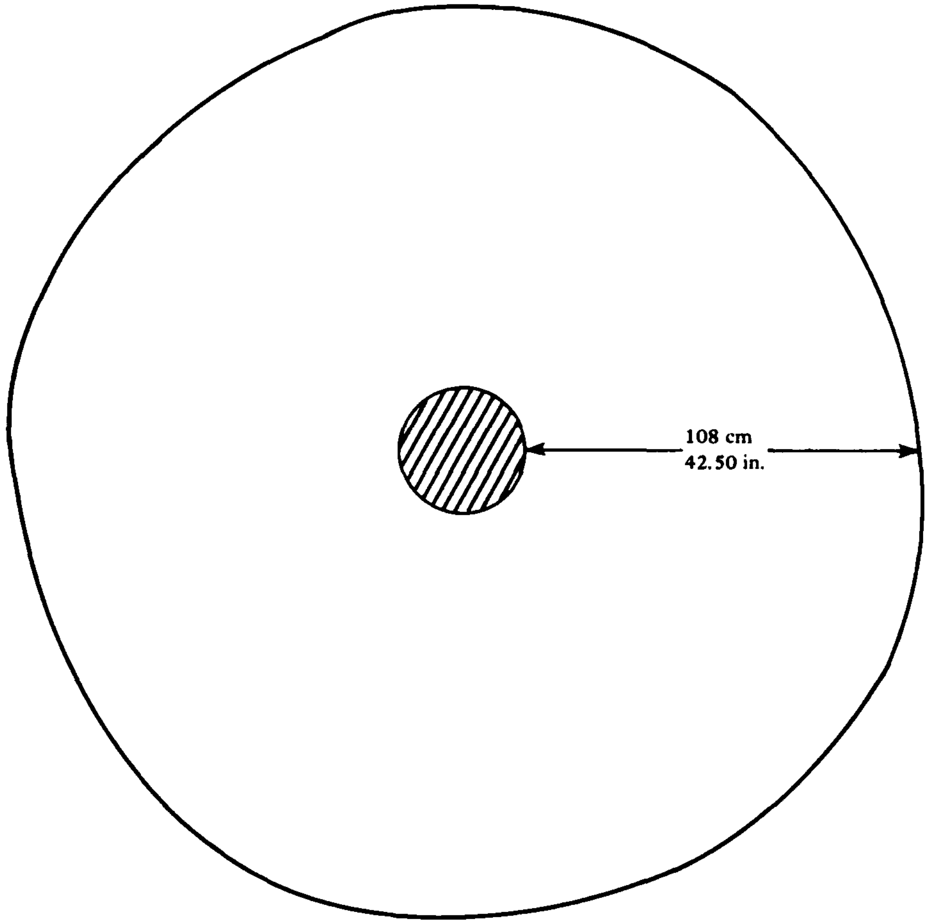


Test 11 - Q = 2 gpm, C = 0.2-0.25 fps, w = 114 sec/rev

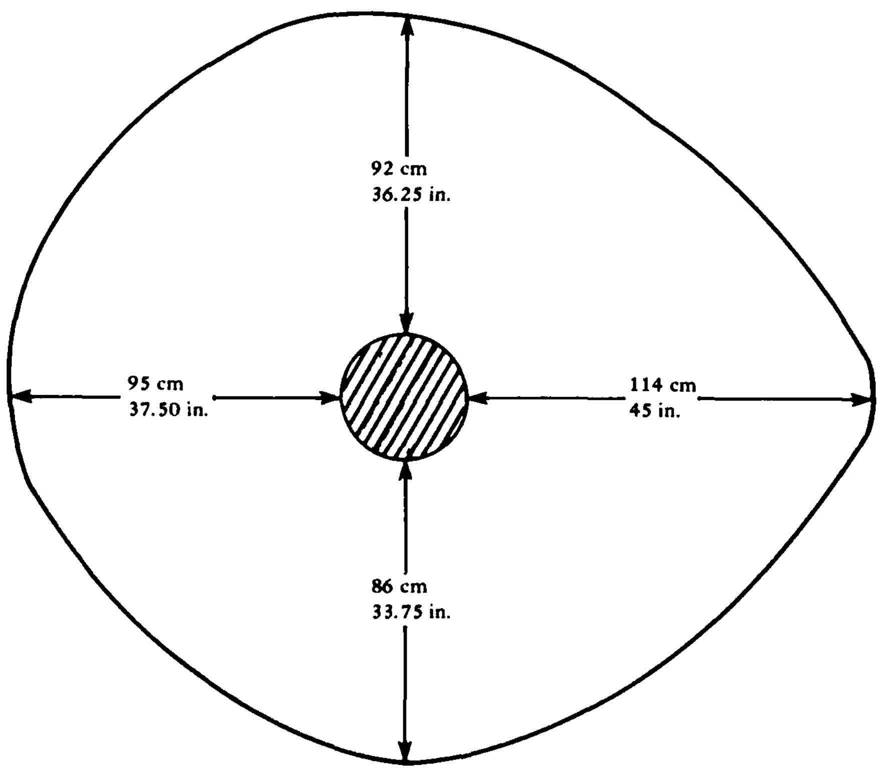


Test 12 - Q = 2 gpm, C = 0.3-0.35 fps, w = 114 sec/rev

Rotating Flow cont'd

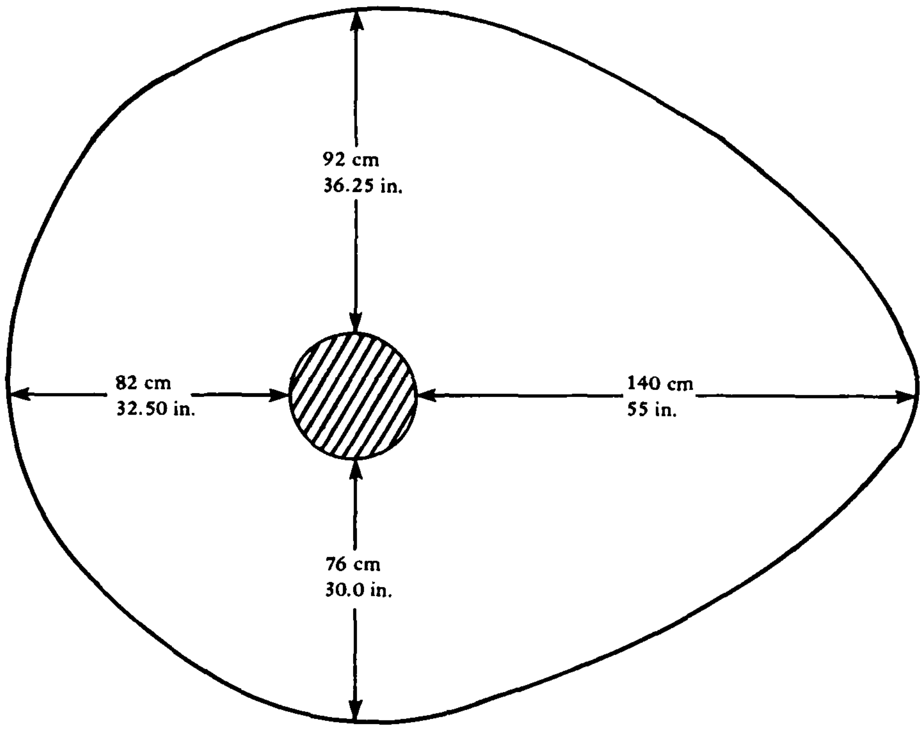


Test 13 - Q = 4 gpm, C = ϕ, w = 114 sec/rev

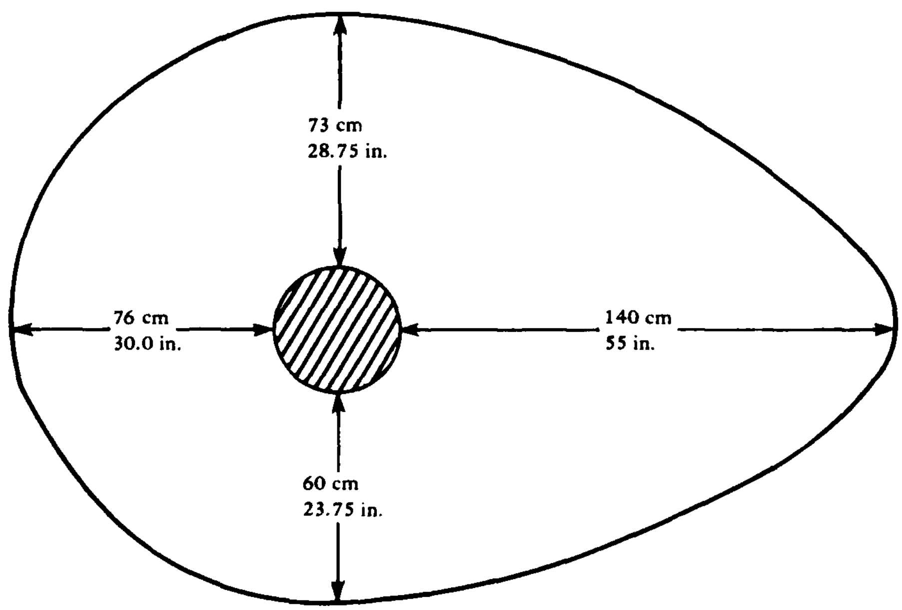


Test 14 - Q = 4 gpm, C = 0.1-0.15 fps, w = 114 sec/rev

Rotating Flow cont'd



Test 15 - Q = 4 gpm, C = 0.2-0.25 fps, w = 114 sec/rev



Test 16 - Q = 4 gpm, C = 0.3-0.35 fps, w = 114 sec/rev

Rotating Flow cont'd

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FLORIDA INSTITUTE OF TECHNOLOGY CE Dept (Kalajian), Melbourne, FL
GEORGIA INSTITUTE OF TECHNOLOGY CE Scol (Kahn), Atlanta, GA; CE Scol (Mazanti), Atlanta, GA
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PORT SAN DIEGO Proj Engr, Port Fac, San Diego, CA
PORTLAND STATE UNIVERSITY Engrg Dept (Migliore), Portland, OR
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